AN INVESTIGATIVE APPROACH TO HARD MACHINING OF INCONEL 718 WITH COATED CARBIDE TOOL

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MECHANICAL ENGINEERING

by

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ABSTRACT

Super alloys sustain good strength at high temperature and pressure conditions. Such materials have high demand in aerospace industry, marine industry, and nuclear power plants. They have a great demand in Nuclear and Aerospace applications because of it retain its properties at temperature over 700 °C. Machinability of nickel based super - alloys is extremely poor, mainly due to their low thermal conductivity, build up edge and self-hardening, which leads to high dynamic cutting forces. They are difficult to machine because, high shear strength, work hardening, precipitation hardening. High abrasive particles in its microstructure and tendency forming chip to weld to tool and form built up edge (BUE) make it more difficult to machine. Friction between tool and material and its low thermal conductivity results in high temperature generation. They have nickel (Ni), chromium (Cr), ferrous (Fe) or Cobalt (Co) as base contains. Small amount of Al, Ti, Nb, Ta, W, Mo added to this alloys to sustain at high temperature. Chromium is important alloying element in order to obtain the hot corrosion resistance property. Due to these factors the tool wear is extremely high and increasing the tool life by minutes is an enormous success. To overcome this situation, various materials have been developed for Inconel 718 machining. Though ceramic tools, silicon carbide whiskers, reinforced alumina tools, carbide tools have been used to machine Inconel 718 but they have failed to produce good surface, better accuracy and minimum tool wear.

The present study is to improvise the surface roughness, reduce tool wear and create better machining parameters for extensive use of the material. Taguchi methodology, Grey relational analysis (GRA) and Response Surface Methodology (RSM) have been used to analyze the cutting parameters and determine better response parameters for the machining characteristics of Inconel 718. The tools taken for machining are tungsten carbide tool and ceramics tool which are found to be suitable tools for improving the machinability of Inconel 718. Coating (AlTiCrN) of tungsten carbide tool has been developed to increase the tool life and provide better machining features on Inconel 718. The coated tool is compared with cryogenic treated tools and ceramic tool to find its suitability over machining Inconel 718.

Key Words: Tungsten Carbide, Ceramics, PVD Coating, ANOVA, GRA

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1. INTRODUCTION

In the industries that require high performance alloys for aerospace, energy production, automotive and biomedical industries, it is important for mission-critical components to perform at aggressive working conditions. Some application in these industries require products to withstand high thermal and mechanical loading conditions for extensive amount of time. For such application's conventional materials like aluminium and steel may not perform, and reliability and durability issues can arise. In these cases, using more advanced material can be advantageous in long run and less costly too [2]. Nickel based superalloys constitute a significant portion of these materials due to their longevity after extended exposures to extreme thermomechanical loads. However, utilizing this superior quality material comes at a sizable cost and machining becomes too difficult. Inconel 718 is one such nickel-based alloy which is characterized by high strength, good oxidation, fatigue and creep resistance at high temperature. These mechanical properties are of great interest in machining area but results in an added difficulty to machine. Its hardening tendency low thermal conductivity and high strength involve cutting processes with high forces and temperatures values. The machining of these materials, accordingly, is associated with low machinability and productivity, where tool wear, finishing accuracy and/or high production costs greatly limit the efficiency [8]. Although there are multiple machining techniques used in present, but the most common method is milling. The milling process is highly complex due to the variation in cutting force, multitooth interrupted chipping and non-uniform loading and remains as a field yet to be explored further. The study has to be performed for finding out the various parameters dealt with machining of Inconel 718 and the specific coated tool to be used to minimize tool wear and increase tool life. Hence, the coated tool to be used is to be studied specifically for dealing with the hard to cut material Inconel 718 which can only perform better machinability in wet conditions.

1.1 Hard Machining

Hard machining is the concept of machining materials whose hardness value is above 35 HRC and primarily ranges from 35-68 HRC. These materials are being used in components which need high tensile strength, rigidity, high fatigue loading, high thermal shock resistance, high chemical stability, high resistance to corrosion. The

machining of these materials is associated with high tool wear, low surface roughness, low cost, efficiency, low finishing and poor machinability [30]. However, some tools have been developed to overcome these conditions and provide better features and characteristics to the machining parameters.

1.2 Inconel 718

It is a nickel based super alloy with excellent high strength and mechanical properties at elevated temperatures and cryogenic temperatures. It can be readily worked, and age hardened. Its temperature at high strength ranges from -253°C to 705°C. It is used in the field of cryogenic tanks, gas turbine components, high pressure vessels, rocket jet fuel engines, submarines, ships, heavy framed tanks, etc. The mechanical properties and chemical composition of Inconel 718 is shown in Table 1.1 and Table 1.2 respectively.

Table 1.1 Mechanical properties of Inconel 718

Yield Point (MPa)	Hardness (HRC)	Elongation (%)	Ultimate Strength (MPa)
1041-1160	35-45	14-19	1260-1390

Table 1.2 Chemical Composition of Inconel 718 (wt%) [4]

Elements	Ti	Al	Mb	Mn	Co	C	Fe	Si	Cb	Cr	Ni
Percentage	0.6	0.8	3.0	0.35	1.0	0.08	17.0	0.35	5.0	19.0	52.82

In this section, it is drawn that Inconel 718 is super alloy with rich in nickel content which is a difficult to cut material. Hard machining is being done using CNC milling machine which will have close dimensional tolerance, better accuracy and good machining features. Tungsten carbide tool and ceramics tool have been taken for machining Inconel 718. The former tool has a high abrasion resistant and can withstand higher temperatures than high speed steel. The latter tool possesses high melting points, excellent hardness and good wear resistance.

2. LITERATURE REVIEW

The research articles has been reviewed taking into account the most recent work related to the research work that has been executed. The following are the views of the authors:

Lohithaksha M Maiyar et al., (2013) explored the optimization of end milling operation for Inconel 718 with multiple response parameters based on the grey relational analysis and taguchi technique. Experimental runs were performed based on Taguchi method of L9 orthogonal array. Parameters such as feed rate, cutting speed and depth of cut are considered for optimization of multiple variable characteristics as material removal rate and surface roughness. The grey relational analysis is used to solve the end milling process for grey relational grade with the multiple performance characteristics.

R.Thirumalai et al., (2013) proposed multicriteria decision making (MCDM) for selecting a single solution from a set of non-dominated solutions. Six objective functions that are surface roughness (Ra), flank wear (Vb), tool life (TL), cutting force (Fc), power consumption (P), and MRR (MRR) are considered as attributes against the process variables of cutting speed, feed and depth of cut. Three steps have been utilized in MCDM models to obtain the ranking of alternatives: (1) determine the relevant criteria and alternatives, (2) attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria, (3) process the numerical values to determine a ranking score of each alternative. The higher ranked solution is selected as the best solution for machining Inconel 718.

Y.Kaynak et al., (2013) discussed tool-wear behaviour and cutting forces in machining of NiTi shape memory alloys (SMAs) under various machining conditions, namely dry, preheated, and cryogenic cooling at three different cutting speeds. Obtained results prove that cryogenic cooling plays a significant role on reducing notch wear at higher cutting speeds in comparison with machining under dry and preheated conditions.

D.Fernandez et al., (2014) presented a comparison between different cooling methods in turning of Inconel 718, which is the most commonly used nickel based

alloy in the industry. Tool life and workpiece surface finish has been analyzed in each case, searching the benefits and limitations of each cooling technique. The results revealed the possibility of replacing conventional pollutant cooling fluids by more other ecologically friendly alternatives.

Durul Ulutan et al., (2015) studied an alternative glance at the bigger picture, providing an insight toward a generalized model that directly addresses the industrial concern of process cost. Solid carbide and ceramic tools, which are known to be heavily utilized in manufacturing gas turbine components, are investigated by their performance as well as the relative cost they induce during end milling the gamma-prime strengthened nickel based superalloy. First, the performance of solid carbide tools with no coating are compared to those with coatings of different material and cost, through a set of tool life experiments at industrially applicable machining conditions.

Kejia Zhuang et al., (2015) discussed the performance of ceramic cutting tool insert tools over two assisted machining conditions: plasma preheating and cryogenic assisted cooling conditions. The plasma nozzle placed in front of the cutting zone is used to soften the material while the liquid nitrogen flow located in the cutting area is used to reduce the cutting temperatures in the contact area. With these two assisted techniques the notch wear and the surface microstructure including surface roughness and micro-hardness are assessed with conventional machining. The experimental results proved that notch wear occurs during dry and plasma enhanced machining (PEM) while it is rarely seen in cryogenic assisted cooling.

F.Barthelma et al., (2016) discussed the development of hard coatings in conjunction with suitable substrate material, cutting edge preparation and finishing systems show an improvement in the machining of nickel based alloys . It was seen that with a polishing time of 8 min and using a fine sized medium (0.4-0.8 mm) the roughness in chip spaces as well as on cutting edges can be reduced.

Tatsuya Sugihara et al., (2016) had carried study on the tool life of CBN and the high speed machining over 100 m/min of Inconel 718. Even the surface topography on the rake surface of the tool on the crater wear and the relationship between the surface roughness of the rake face and the wear resistance was

investigated. It was seen that smoother rake face significantly reduce the progress of crater wear indicating that crater wear resistance has a strong correlation with the surface roughness of tool rake face. Even in high speed machining the polished surface not only prevents crater wear but also supresses the local adhesion.

D Grguras et al., (2019) analysed the high speed milling process, using full body ceramic end milling tools in parallel to carbide tools. Tool life of ceramic tools was compared with tool life of more widely used carbide tools when milling two different difficult-to-cut materials, i. e. nickel based alloy Inconel 718 and austenitic stainless steel 316L, under different cooling lubrication conditions. In addition, surface integrity and cost analysis were taken into account.

Daniel Finkeldei et al., (2019) found that high-speed machining, however, generates high temperatures inside the shear zone of the cutting process, which heats the tool and workpiece and reduces cutting forces as well as tool-wear. As a result, the use of ceramic end milling tools can increase the productivity of the machining process. In rough end milling of Inconel 718, ceramic cutting tools can raise the performance of the machining process. For a theoretical consideration with a slot milling and trimming process, ceramic end milling tools could increase the process performance up to 58 %.

In this section, the findings are deeply studied and can be concluded into the following:

- Coated tool gives better performance in improving the machinability.
- CNC milling can be used for machining Inconel 718 for improving surface roughness.
- Al-Ti-Cr-N coating of the tool can be used to increase tool life.
- Optimization of cutting parameters have to be determined in order to reduce surface roughness and obtain lower tool wear.
- Cryogenic treated insert increases the hardness of the tool.
- Low speed and use of coolant can be carried out for effective machining.
- Feed rate, depth of cut and spindle speed are the ideal parameters for machining.
- Taguchi methodology, Grey Relational Analysis and Response Surface Methodology are the optimizing techniques for finding the suitable parameter in machining of Inconel 718.

3. PROBLEM IDENTIFICATION AND STATEMENT

The research problems that are considered for this research work being carried out:

- Due to the superior qualities of the Inconel 718 which makes it suitable to be used at elevated temperature (649ºC) is an important challenge to machine the surface as it results in tool wear, abrupt cutting conditions and improper surface finish.
- Low thermal conductivity, rapid work hardening, ability to react with tool materials under atmospheric conditions, formation of built-up edge, weld to the cutting edges and presence of abrasive carbides in their microstructure causes poor machinability of these materials and restrict the wider usage of Inconel 718.
- The idea is to investigate how far the surface can be machined and up to what depth keeping in mind the machining parameters and lubrication properties.
- CNC milling is one way to improve the machining of this Inconel 718 due to its high speed accuracy, close dimensional tolerances, better surface finish and good lubrication for the cutting tool. The cutting tool to be used has to be coated properly which minimizes tool wear and increases productivity.

Owing to the prevailing research problems and the findings that are to be met, the research has been narrowed down to the title ‘An investigative approach to hard machining of Inconel 718 with coated carbide tool.’

4. OBJECTIVES AND RESEARCH METHODOLOGIES

The objectives for the proposed research work are mentioned,

1. To determine the effect of cutting parameters during machinability of Inconel 718.
2. To minimize surface roughness and reduce tool wear during machining of Inconel 718.
3. To optimize the machining parameters using Taguchi, Grey relational analysis and Response surface methodology.
4. To study the characterization of cutting tool insert to understand the tool performance during machining.

4.1 Research Methodology

The research is being done in achieving objective 1 using an experimental set-up with Inconel 718 as workpiece and tungsten carbide and ceramic as cutting tool insert. Minitab software is being used in achieving objective 2. For achieving objective 3, analysis of variance and grey relational analysis technique with mathematical equations has been used to analyse the observed data. Validation of results will be done towards achieving objective 4 with two techniques chosen for study.

The experiment was conducted on a BOSCH CNC vertical milling machine shown in Figure 4.1 under wet machining condition. The machine has a maximum cutting speed of 1800 rpm, feed rate of 10 m/min and 25-kW drive motor. The work piece shown in Figure 4.2 used was Inconel 718, a Nickel-based super alloy with dimension of (75×50×40) mm^3 block. The work piece was placed on the machine worktable with the help of a fixture for stability of the work piece.

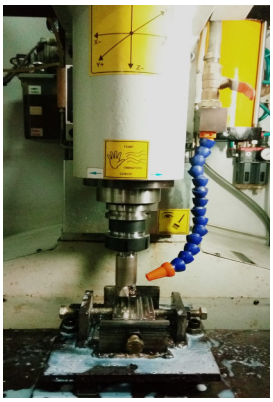


Figure 4.1 Experimental set-up

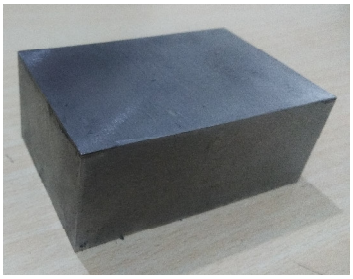


Figure 4.2 Workpiece (Inconel 718)

A fixture shown in Figure 4.3 is specifically prepared to hold the workpiece in order to reduce the noise and vibrating conditions. The fixture consists of a main plate, support plate and a slot plate. All the holes in the fixture are M12 tapped hole.

The dimensions of the fixture are:

- Main plate: 200×200×12 mm^3
- Support plate: 80×12×50 mm^3
- Slot plate: 100×100×12 mm^3
- Slot size: 100×80×3 mm^3
- Hole: M12 tapped holes

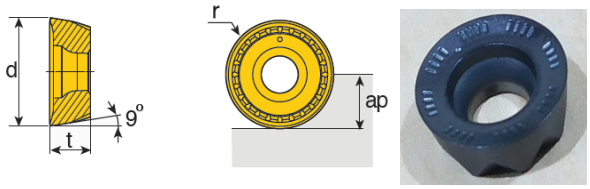
Figure 4.3 Fixture of the workpiece (Inconel 718)

The experimental setup for the end milling operation of the work piece is shown in Figure 4.2. One tool insert is a small round tool insert of tungsten carbide shown in Figure 4.4c described by RYMX 1004-ML of grade TT3540. The second tool insert used is ceramic shown in Figure 4.5c of AS20 grade which is round in size and described by RPGX 1204 CH AS20. Surface Roughness is measured using Surface Roughness Tester is shown in Figure 4.6. The average value of the surface roughness is taken in microns. Tool wear is determined using Tool Maker's Microscope is shown in Figure 4.7 and the value is noted down in millimeter.

4.2 Experimental requirements

4.2.1 Cutting tools

The detailed description of the Tungsten Carbide tool insert seen in Fig 4.4 has been used for machining Inconel 718.



(a) (b) (c)

Figure 4.4 (a) Side view (b) Top view (c) Actual pic of Tungsten Carbide Tool insert

d = 10 mm
t = 4 mm
r = 4 mm
a_p = 5 mm

The detailed specification of the Ceramics tool insert seen in Fig 4.5 has been used for machining Inconel 718.

RE = 6.35
IC = 6.70
S = 4.76
APMX = 6.000

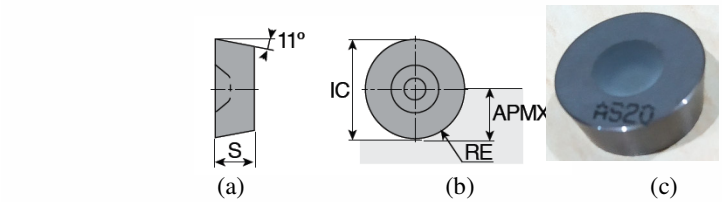


Figure 4.5 (a) Side view (b) Top view (c) Actual pic of Ceramics Tool insert

4.2.2 Cutting parameters

The three cutting parameters optimized in this investigation are:

- Cutting speed
- Feed Rate
- Depth of Cut

Cutting speed: It is the relative velocity between the cutting tool and the surface of the work piece it is operating on. The unit of cutting velocity is revolutions per minute (rpm). The values of the different levels for level 1, 2 and 3 are 500, 600 and 700 respectively.

Feed Rate: It is the relative velocity at which the cutter is advanced along the work piece. The unit of feed rate is millimeters per min (mm/min). The values of the different levels for level 1, 2 and 3 are 10, 15 and 20 respectively.

Depth of Cut: The thickness that is removed as a work piece is being machined. The unit of depth of cut is millimeters (mm). The values of the different levels for level 1, 2 and 3 are 0.2, 0.4 and 0.6 respectively.

4.2.3 Output parameters

The average surface roughness (Ra) value is recorded in microns. Tool wear of the tool tool insert is also calculated.

Surface Roughness: Surface roughness also known as surface profile (Ra) is a measurement of surface finish. It is a topography at a scale that might be consider

"texture" on the surface. Surface roughness is a quantitative calculation of the relative roughness of a linear profile area expressed as a single numeric parameter (Ra).

Instrument used: Surface Profilometer. Surface profilometer is the measuring instrument used to measure the roughness of a surface and gives the result as the average distance between the two peeks of the regular profile.

Figure 4.6 Mitutoyo SJ210 surface roughness tester

Tool Wear: It describes the gradual failure of cutting tools due to regular operation. It is a term often associated with tipped tools, tool bits or drill bits that are used with machine tools. Instrument used: Tool maker's Microscope shown in Figure 4.7 is used for the measuring very small distances on objects like peak distance of the bolt treads, gear tooth, etc.

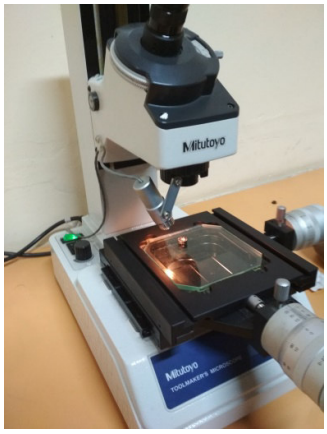


Figure 4.7 Mitutoyo Tool Maker's Microscope

The specifications of the Tool Maker's Microscope are as follows:

•Model- TM505/TM505R with magnification of 15x
•Dimensions- 152 × 152 mm
•Stage Glass Size - 96 × 96 mm
•Feeding Range - 50 × 50 mm

4.2.4 Cryogenic treatment

The cryogenic treatment unit shown in Figure 4.8 (Facility used in Centre for Cryogenic Technology, IISc Bangalore) has a multi-walled stainless steel container with the inner space filled with Polyurethane foam. The upper cover is made of stainless steel which has a double end shaft fan-motor assembly mounted centrally. The liquid nitrogen connects the valves, feed through, outlet connections and pressure gauges are all mounted on the upper cover. Under the upper cover, a cylindrical buffer tank is mounted where the supplied liquid nitrogen gets accumulated and vaporized where vapours are vented through a vent pipe. The shaft of the fan motor assembly passes through the buffer tank and has mounted fan blades on both the sides. To ensure better transfer of heat, a copper disc has been fixed to the bottom of the buffer tank. To the bottom of the copper disc are fixed aluminium fins circumferentially to ensure cooling of the space by forced convection inside the chamber where cryotreatment has undergone.

Figure 4.8 Cryotreatment system

When metals are gradually cooled to cryogenic temperatures, they are soaked for a longer period and then warmed to ambient temperature at a predetermined rate, whereby the structure of the lattice atoms changes due to stresses being relieved

during treatment of cryogenic cycle. A typical cryotreatment cycle shown in Figure 4.9 involves mainly three phases where the metal samples are cooled gradually to cryogenic temperature (cooling period), holding for prolonged length of time (soak time) and gradually warming (warming time) to ambient temperature. In normal practice, a complete cryotreatment cycle takes around 50 hours with 5 hours of cooling, 36 hours of soaking and 9 hours of warming. 225 lt of nitrogen is used during entire cycle to cryotreat the tool insert kept in the cryotreatment chamber unit.

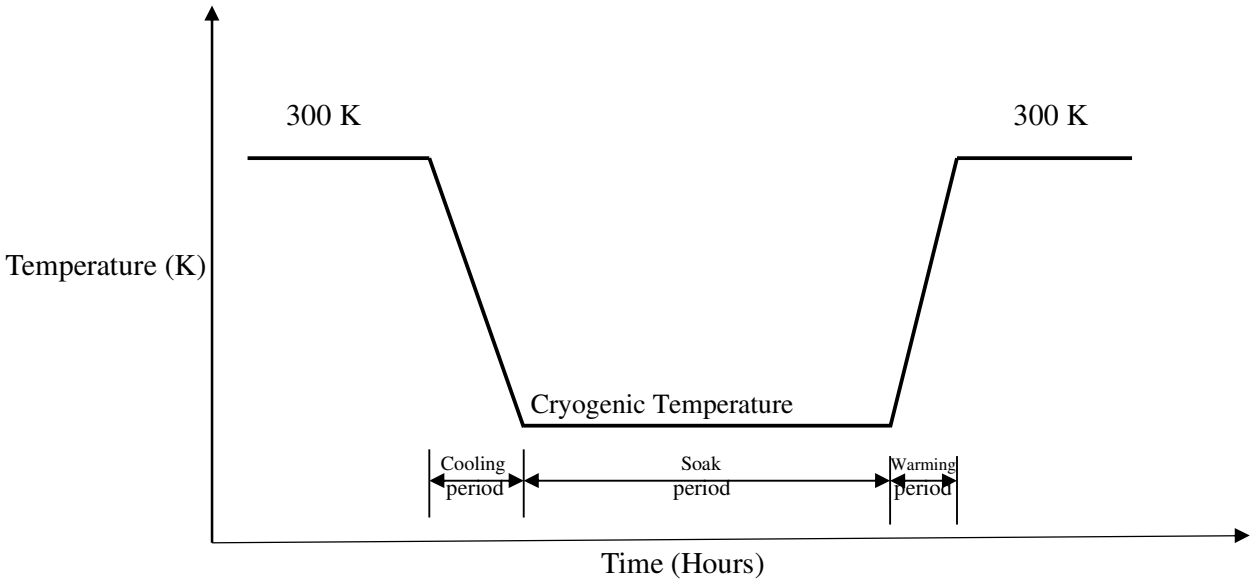


Figure 4.9 Cryotreatment cycle

After the cryotreatment, the tool insert were taken to advanced machining lab for machining Inconel 718. Table 6.4 and Table 6.5 shows the experimentation carried out on Inconel 718 using Cryogenic Treated Tungsten Carbide tool insert and Cryogenic Treated Ceramic tool insert.

4.2.5 Physical Vapor Deposition (PVD) coating

The PVD coating of Tungsten Carbide tool insert was carried out in sputtering machine present in National Nano Fabrication lab, IISc Bangalore shown in Figure 4.10, using sputtering method of Physical Vapour Deposition (PVD) using three different cathodes known as targets which are AlN, TiN and CrN. Sputtering technique of Physical Vapour Deposition (PVD) is an evaporation technique in which

an electric arc is used to vaporise material from a cathode. The procedure begins with striking of a high current low voltage arc on the outside surface of the cathode known as the target. This creates a small, typically wide, high energetic area known as cathode spots. The localized temperature at the cathode spot, high energised area is extremely high which results in a carter on the cathode surface. Reactive gas such as Argon (Ar) or Nitrogen (N) is being supplied into the chamber during the process of evaporation. Ionization, excitation and dissociation will occur during the interaction with the reactive gas and a compound film will be deposited on the surface of the tool insert. The substrate holder is shown in Figure 4.11.

Figure 4.10 Hind High Vacuum Glove Box
PVD Sputtering Machine, CENSE, IISC Bangalore

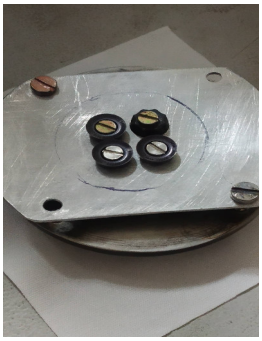


Figure 4.11 Substrate holder

The specifications of the PVD machine in which coating was carried over the tool insert:

• 4 circular shaped substrate holders of 6 inch in diameter.
• Coating consistency up to 4 inch substrate size with rotation.
• Consistency up to 1.5 inch circular area for stationary deposition.
• Target dimensions are 3 mm diameter and less than or equal to 6 mm thickness.
• Substrate will be heated up to 600°C. Using localised heating systems.
• Substrate holders will be having planetary rotation which offers very high film uniformity.
• Rotary dry pump which provides a pumping speed of 1670 Ltr / min.
• Turbo Molecular pump provides very high vacuum in a speed of 1450 Ltr/sec, 31500 rev/min and gives ultimate vacuum of 8×10^{-8} T.
• RF and DC bias voltage.

5. ACCOMPLISHMENT OF THE PROPOSED WORK

The experiment is carried out based on a Taguchi L9 orthogonal array taking cutting parameters displayed in Table 5.1 as spindle speed, feed rate and depth of cut while response parameters are surface roughness and tool wear displayed in Table 5.2.

Table 5.1 Cutting parameters and their levels

Parameter	Unit	Symbol	Level 1	Level 2	Level 3
Cutting Speed	rpm	v	500	600	700
Feed Rate	mm/min	f	10	15	20
Depth of cut	mm	d	0.2	0.4	0.6

Table 5.2 Experimentation with the machining and response parameters using tungsten carbide tool insert

Runs	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)					Tool wear (mm)		
				1st reading	2nd reading	3rd reading	4th reading	Mean	1st reading	2nd reading	Mean
1	500	10	0.2	0.780	0.760	0.800	0.790	0.783	0.049	0.051	0.050
2	500	15	0.4	0.610	0.630	0.640	0.620	0.625	0.026	0.024	0.025
3	500	20	0.6	0.410	0.420	0.450	0.470	0.438	0.058	0.056	0.057
4	600	10	0.4	0.870	0.860	0.890	0.950	0.893	0.039	0.041	0.040
5	600	15	0.6	0.750	0.780	0.770	0.810	0.778	0.147	0.149	0.148
6	600	20	0.2	0.370	0.350	0.340	0.390	0.363	0.051	0.049	0.050
7	700	10	0.6	0.520	0.510	0.560	0.570	0.540	0.404	0.406	0.405
8	700	15	0.2	0.240	0.280	0.260	0.290	0.268	0.049	0.051	0.050
9	700	20	0.4	0.480	0.460	0.470	0.500	0.478	0.024	0.026	0.025

Table 5.3 Experimentation with the machining and response parameters using ceramics tool insert

Runs	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)					Tool wear (mm)		
				1st reading	2nd reading	3rd reading	4th reading	Mean	1st reading	2nd reading	Mean
1	500	10	0.2	1.102	0.885	0.875	0.882	0.936	0.033	0.032	0.033
2	500	15	0.4	0.815	1.324	0.871	0.822	0.958	0.041	0.040	0.041
3	500	20	0.6	1.316	1.102	1.576	1.346	1.335	0.031	0.030	0.031
4	600	10	0.4	1.470	1.225	0.939	1.220	1.214	0.471	0.470	0.471
5	600	15	0.6	0.766	0.904	0.886	0.864	0.855	0.478	0.477	0.478
6	600	20	0.2	0.871	0.759	0.738	0.752	0.780	0.448	0.447	0.448
7	700	10	0.6	0.962	1.018	0.956	0.927	0.966	0.053	0.052	0.053
8	700	15	0.2	0.876	0.767	0.907	0.865	0.854	0.013	0.012	0.013
9	700	20	0.4	0.780	0.618	0.880	0.782	0.765	0.157	0.156	0.157

The Table 5.2 is displaying the observed values taken during the experimentation of machining of Inconel 718 using Tungsten Carbide tool where three values of surface roughness were found along the path of the tool and two readings of tool wear are

noted at different positions to find the tool wear. The below Table 5.3 is displaying the experimentation of machining of Inconel 718 using Ceramics tool and readings are noted in similar manner.

Table 5.4 Experimentation with the machining and response parameters using cryogenic treated tungsten carbide tool insert

Runs	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)					Tool wear (mm)		
				1st reading	2nd reading	3rd reading	4th reading	Mean	1st reading	2nd reading	Mean
1	500	10	0.2	1.055	1.264	0.723	1.011	1.013	0.086	0.085	0.086
2	500	15	0.4	1.250	1.255	1.257	1.144	1.227	0.101	0.103	0.102
3	500	20	0.6	1.215	1.548	0.992	0.995	1.188	0.041	0.043	0.042
4	600	10	0.4	0.917	0.898	0.532	0.878	0.806	0.021	0.023	0.022
5	600	15	0.6	1.534	1.539	1.529	1.535	1.534	0.029	0.031	0.030
6	600	20	0.2	1.487	1.597	0.983	1.490	1.389	0.364	0.366	0.365
7	700	10	0.6	1.218	0.889	0.975	0.989	1.018	2.179	2.181	2.180
8	700	15	0.2	1.080	1.179	1.554	1.148	1.240	1.119	1.221	1.170
9	700	20	0.4	0.990	1.744	0.956	0.989	1.170	0.878	0.877	0.878

Table 5.5 Experimentation with the machining and response parameters using cryogenic treated ceramics tool insert

Runs	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)					Tool wear (mm)		
				1st reading	2nd reading	3rd reading	4th reading	Mean	1st reading	2nd reading	Mean
1	500	10	0.2	1.623	1.627	1.628	1.629	1.627	0.924	0.926	0.925
2	500	15	0.4	1.671	1.672	1.673	1.670	1.672	1.060	1.080	1.070
3	500	20	0.6	1.144	1.146	1.148	1.150	1.147	1.086	1.088	1.087
4	600	10	0.4	1.692	1.696	1.695	1.698	1.695	0.021	0.023	0.022
5	600	15	0.6	1.180	1.182	1.182	1.186	1.183	1.042	1.044	1.043
6	600	20	0.2	0.962	0.961	0.965	0.968	0.964	0.034	0.036	0.035
7	700	10	0.6	1.742	1.745	1.748	1.761	1.749	0.151	0.156	0.154
8	700	15	0.2	0.918	0.892	0.870	0.904	0.896	0.833	0.837	0.835
9	700	20	0.4	1.389	1.381	1.385	1.371	1.382	0.040	0.045	0.043

Table 5.4, Table 5.5 and Table 5.6 are displaying the experimentation of machining of Inconel 718 using Cryogenic Treated Tungsten Carbide tool, Cryogenic Treated Ceramics tool and Coated Tungsten Carbide tool where readings are noted in similar manner as in Table 5.2.

Table 5.6 Experimentation with the machining and response parameters of response surface methodology using coated tungsten carbide tool insert

Runs	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)					Tool wear (mm)		
				1st reading	2nd reading	3rd reading	4th reading	Mean	1st reading	2nd reading	Mean
1	500	10	0.2	0.087	0.086	0.084	0.085	0.086	0.033	0.031	0.032
2	700	10	0.2	0.133	0.043	0.078	0.086	0.085	0.048	0.050	0.049
3	500	20	0.2	0.127	0.124	0.120	0.126	0.124	0.044	0.046	0.045
4	700	20	0.2	0.124	0.130	0.129	0.128	0.128	0.052	0.050	0.051
5	500	10	0.6	0.149	0.143	0.142	0.145	0.145	0.042	0.043	0.043
6	700	10	0.6	0.162	0.168	0.156	0.187	0.168	0.035	0.036	0.036
7	500	20	0.6	0.129	0.126	0.121	0.128	0.126	0.060	0.050	0.055
8	700	20	0.6	0.132	0.138	0.133	0.137	0.135	0.061	0.050	0.056
9	431.8207	15	0.4	0.190	0.176	0.188	0.179	0.183	0.084	0.082	0.083
10	768.1793	15	0.4	0.104	0.099	0.103	0.101	0.102	0.025	0.030	0.028
11	600	6.591036	0.4	0.163	0.161	0.164	0.165	0.163	0.040	0.030	0.035
12	600	23.40896	0.4	0.128	0.127	0.132	0.130	0.129	0.064	0.061	0.063
13	600	15	0.063641	0.090	0.092	0.094	0.095	0.093	0.024	0.026	0.025
14	600	15	0.736359	0.154	0.158	0.156	0.159	0.157	0.056	0.055	0.056
15	600	15	0.4	0.128	0.124	0.123	0.127	0.126	0.064	0.063	0.064
16	600	15	0.4	0.134	0.138	0.144	0.140	0.139	0.059	0.058	0.059
17	600	15	0.4	0.131	0.129	0.133	0.130	0.131	0.062	0.065	0.064
18	600	15	0.4	0.114	0.117	0.118	0.113	0.116	0.061	0.064	0.063
19	600	15	0.4	0.134	0.131	0.132	0.135	0.133	0.064	0.067	0.066
20	600	15	0.4	0.131	0.132	0.134	0.137	0.134	0.063	0.066	0.065

5.1 Grey Relational Analysis (GRA)

Grey relational analysis (GRA), also called Deng's Grey Incidence Analysis model, was developed by a chinese professor Julong Deng of Huazhong University of science and technology. It is a multiobject optimization method to corelate different groups of cutting parameters and decides the distance between the experimental runs. This technique identified the effect of machining parameters on response variables and helps to know the optimal value for the correct experimental run shown in Table 5.7.

Table 5.7 Ranking of the experimental runs through grey relational degree

Tool insert	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)	Tool wear (mm)
Tungsten Carbide	600	15	0.6	0.778	0.148
Ceramics	500	15	0.4	1.672	1.070
Cryogenic treated TC	600	10	0.4	1.214	0.471
Cryogenic treated C	500	15	0.4	1.227	0.102
Coated TC	600	15	0.4	0.133	0.066

5.2 Analysis of variance (ANOVA)

Analysis of Variance (ANOVA) is a parametric statistical technique used to compare datasets. This technique was invented by R.A. Fisher, and is thus often referred to as Fisher's ANOVA, as well. This method showed the effective contribution of the cutting parameters over response variables. It determines how importance will be to determine the response variables in effect to machining parameters. The F-value determines how much difference is the factor from the other groups and p-value < 0.5 is considered to be ideal for proving the parameter effective in signifying the change it brings to response variables.

5.3 Characterization of the coating

The coating was characterized using the facility at Central Manufacturing Technology Institute, Bangalore. The nano indentation technique was used to determine the hardness of the coating found to be 400 mN and modulus of elasticity 231.7 GPa.

5.4 SEM and EDS analysis

The SEM images were taken at Micro and Nano Characterization facility, IISc Bangalore for the study of the tool wear before and after machining Inconel 718 using all the tools which are tungsten carbide, ceramics, cryogenic treated tungsten carbide,

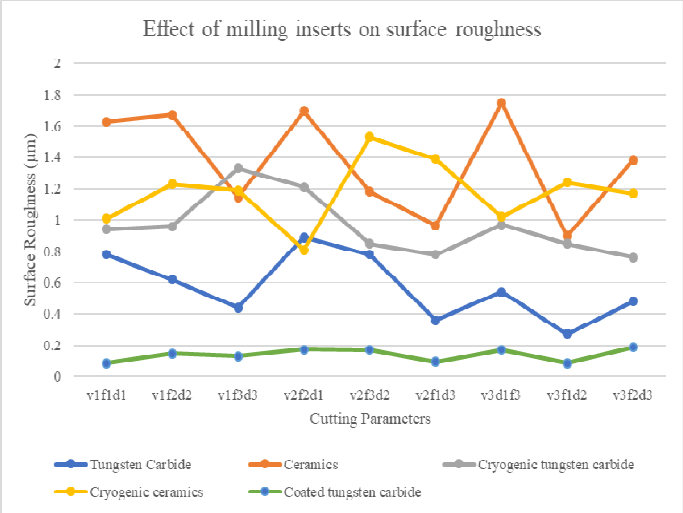
cryogenic treated ceramics and coated tungsten carbide. EDS was done to predict the phase of the cryogenic treated tools of tungsten carbide tool and ceramics tool.

5.5 Linear regression equation

The linear regression equation is generated for each tool being used to machine Inconel 718. The surface roughness and tool wear can be determined at varied cutting speeds, feed rate and depth of cut using the equations generated in the Minitab software. This equation help to find out the surface roughness and tool wear of coated (AlTiCrN) tungsten carbide tool and compare with the coated (TiAlN) tool of Amado Tools company, Bangalore. Thus, it was seen that the coated (AlTiCrN) tungsten carbide tool showed lower surface roughness and tool wear than coated (TiAlN) tool.

6. RESULTS AND DISCUSSION

In this section comparison of the tools has been plotted in graphs and shown their effect on machining Inconel 718 to have minimum surface roughness and low tool wear.



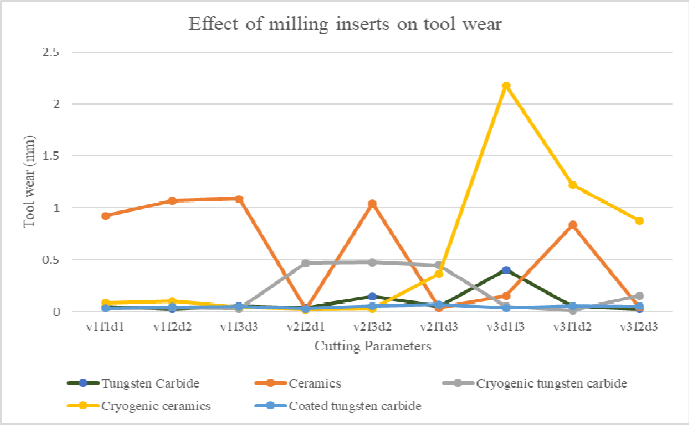
Cutting Speed (v1=500,v2=600 ,v3=700)rpm

Feed Rate (f1=10,f2=15,f3=20) mm/min

Depth of cut (d1=0.2,d2=0.4,d3=0.6)mm

Figure 6.1 Effect of tool inserts on surface roughness

In Figure 6.1 the Coated Tungsten Carbide can be seen has produced lower surface roughness on Inconel 718 than the other tools. Hence proves to be the suitable tool.



Cutting Speed (v1=500,v2=600 ,v3=700)rpm

Feed Rate (f1=10,f2=15,f3=20) mm/min

Depth of cut (d1=0.2,d2=0.4,d3=0.6)mm

Figure 6.2 Effect of tool inserts on tool wear

In Figure 6.2 the Coated Tungsten Carbide can be seen has lower tool wear during machining on Inconel 718 than the other tools. Hence proves to be the suitable tool.

7. CONCLUSION

The following conclusions are drawn from the research work that has been carried out:

- The machinability of Inconel 718 has been greatly enhanced by providing optimal control parameters-cutting speed, feed rate and depth of cut which are the suitable conditions for providing minimum surface roughness (0.103µm) and low tool wear (0.011 mm).
- The response variables-surface roughness and tool wear have a greater impact due to the suitable machining parameters which was proved by analysis of variance for S/N ratio.
- Among Tungsten Carbide tool and Ceramics tool, Tungsten Carbide tool proved to be better than the other in improving the machining of Inconel 718.
- The Cryogenic Treated tool inserts though increased the wear resistance of the inserts, didn't show better results than Tungsten Carbide tool insert.
- Taguchi methodology optimized the control parameters and helped to determine the influence parameters which had an effect on the response variables.
- Grey Relational Analysis optimized the control parameters and response variables to determine the suitable parameters required for machining Inconel 718 using the tool inserts.
- Response Surface Methodology envisage the multiple objective function for determining the cutting parameters required for Coated Tungsten Carbide tool.
- Coated Tungsten Carbide tool proved to be a better cutting tool in improving the machinability of Inconel 718 than the Cryogenic Treated tools and Ceramic tool.

8. SCOPE FOR FUTURE WORK

The scope for further carrying out the research work has been given below:

- The coated tool can be compared with cubic boron nitride (next hardest tool to diamond) for analyzing tool performance.
- Different types of coolants can be used for heat reduction between tool workpiece interface which impacts tool wear.
- Other cutting parameters such as material removal rate, temperature, cutting forces can be optimized for better machining conditions.

BIBLIOGRAPHY

In this research work that has been carried out, there are over 60 research papers that have been studied and few has been listed below:

[1] Thirumalai R and Senthilkumaar J.S., "Multi-criteria decision making in the selection of machining parameters for Inconel 718," *Journal of Mechanical Science and Technology*, vol 27 issue 4,1109-1116, 2013.

[2] Alagan N.T., Beno T. and Wretland A., "Investigation of modified cutting tool insert with forced coolant application in machining of Alloy 718," *Procedia CIRP 42*, pp 481 – 486, 2016.

[3] Maiyar L. M, Dr.Ramanujam R, Venkatesan K. and Dr.Jerald J, "Optimization of Machining Parameters for End Milling of Inconel 718 Super Alloy Using Taguchi Based Grey Relational Analysis," *International Conference on design and manufacturing, Procedia Engineering 64*, pp 1276 – 1282, 2013.

[4] Fernandez D., Navas V.G., Sanda A. and Bengoetxea I., 'Comparison of machining inconel 718 with conventional and suatainable coolant," *MM Science Journal*, vol 514, pp 506-510, 2014.

[5] Ulutan D., Pleta A., Henderson A. and Mears L., "Comparison and cost optimization of solid tool life in end milling nickel based super alloy", *43 Proceeding of North American Manufacturing Research*, Vol 1, pp 522-533, 2015.

[6] Zhuang K., Zhang X., Zhu D. and Ding H., "Employing preheating and cooling assisted technologies in machining of Inconel 718 with ceramic cutting tools: towards reducing tool wear and improving surface integrity," *International Journal of Advance Manufacturing Technology*, vol 80 , pp 1815-1822, 2015.

[7] Barthelma F., Frank H., Schiffler M., and Bartsch A., "Hard coatings to improve the machining of nickel based materials," *Procedia CIRP 46* , pp 294 – 298, 2016.

[8] Sugihara T., Takemura S. and Enomoto T., "Study on high-speed machining of Inconel 718 focusing on tool surface topography of CBN cutting tool," *International Journal of Advance Manufacturing Technology*, vol 87, pp 9–17, 2016.

[9] Grguras D.A., Kern M.A. and Pusavec F, "Cutting performance of solid ceramic and carbide end milling tools in machining of nickel based alloy Inconel 718 and stainless steel 316L", *Advances in production engineering and management*, vol 14, pp 27-38, 2019.

[10] Thakur D, Ramamoorthy B and Vijayaraghavan L, "Influence of different post treatments on Tungsten Carbide-Cobalt inserts," International Journal on Materials Letters, vol. 62, pp. 4403-4406, 2008.

[11] Kulkarni A.P., Joshi G.G., Karekar A and Sargade V.G., "Investigation on cutting temperature and cutting force in turning AISI 304 austenitic stainless steel using AlTiCrN coated carbide insert," International journal of Machining and Machinability of Materials, vol. 15, pp. 147-156, 2014.

[12] Kulkarni A, Patel N G and Sargade V G, "Investigation of microstructure and mechanical properties of AlTiCrN, AlCrN coating deposited by advanced sputtering technique," Conference on Advances in Intelligent Systems Research, vol. 137, pp. 311-315, 2017.

[13] Kamdani K, Hasan S, Ashaary A.F.I.A., Mohd Lajis A and Rahim E.A, "Study on tool wear and wear mechanisms of end milling Nickel-based alloy", *Malaysian Journal Tribology*, Vol 21, pp 82-92, 2019.

[14] Finkeldei D, Sexauer M and Bleicher F, "*End milling of Inconel 718 using Si_3N_4 ceramic cutting tools*", Procedia CIRP, vol 81, pp 1131-1135, 2019.

[15] Zhuang K., Zhang X., Zhu D. and Ding H., "Employing preheating and cooling assisted technologies in machining of Inconel 718 with ceramic cutting tools: towards reducing tool wear and improving surface integrity," *International Journal of Advance Manufacturing Technology*, vol 80 , pp 1815-1822, 2015.

APPENDIX A

1. LIST OF PUBLICATIONS IN SCOPUS INDEXED JOURNALS

i. **Rout I.S.**, Palpandian P, "A Review on parametric study of hard machining of Inconel 718 using coated carbide tool", *Advanced Science, Engineering and Medicine*, vol 10, pp 234-239, 2018. DOI:10.1166/asem.2018.2131

Link:
https://www.ingentaconnect.com/content/asp/asem/2018/00000010/f0030003/art00003;jsessionid=e2vto56ovxw3.x-ic-live-03

ii. **Rout I.S.**, Palpandian P, "Selection of cutting parameters for the machinability of Inconel 718 using Grey Relational Analysis," *MATEC Web of Conferences*, Vol 172 (04004), 2018. DOI: https://doi.org/10.1051/matecconf/201817204004

Link:
https://www.matec-onferences.org/articles/matecconf/abs/2018/31/matecconf_icdams2018_04004/matecconf_icdams2018_04004.html

iii. Palpandian P, **Rout I.S.**, "Parametric Investigation of machining parameters in determining the machinability of Inconel 718 using taguchi technique and grey relational analysis," *Procedia Computer Science*, Vol 133, pp 786-792, 2018. DOI: 10.1016/j.procs.2018.07.118

Link: https://www.sciencedirect.com/science/article/pii/S1877050918310718

iv. **Rout I.S.**, Palpandian P, Raj A, Misra S, Patil V, "Parametric analysis of response variables for improving the machining characteristics of Inconel 718 using ceramic inserts," *International Journal of Mechanical and Production Engineering Research and Development*, Vol 9 special issue, pp 106-113, 2009.

Link:
http://www.tjprc.org/conferencearchives.php?tid=&e_type=&jname=&year=&keyword=Ivan+Sunit+Rout &from_date=&to_date=&journal=

v. **Rout I.S.**, Palpandian P, Raj A, Lobo Ivan K, C Antony S, "An approach for the investigation of cutting parameters to improve the machinability of Inconel 718 using cryogenic treated tungsten carbide," *International Journal of Mechanical and Production Engineering Research and Development*, Vol 10 special issue, pp 1-11, 2020.

Link: http://www.tjprc.org/conference-archives.php?tid=&e_type=&jname=&year=2020&keyword=&from_date=&to_date=&journal=

2. LIST OF PAPERS PRESENTED IN INTERNATIONAL CONFERENCES

i. Paper titled "A Review on parametric study of hard machining of Inconel 718 using coated carbide tool" at the *Second International Conference on Mechanical and Manufacturing Engineering* held during 6-7 April 2017 organized by Department of Mechanical Engineering, Srichandrasekharendra saraswathi viswa mahavidyalaya, Enathur, Kanchipuram, Tamilnadu.

Link: https://www.technicalsymposium.com/technicalsymposium2017_Jan_3.html

ii. Paper titled "Selection of cutting parameters for the machinability of Inconel 718 using Grey Relational Analysis" at the *3rd International Conference on Design, Analysis, Manufacturing and Simulation* held during 6-7 April 2018 organized by Department of Mechanical and Automobile Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamilnadu.

Link:
http://www.knowafest.com/college-fests/events/2017/11/2302-3rd-international-conference-design-analysis-manufacturing-simulation-icdams-2018-saveetha-school-engineering-chennai

iii. Paper titled "An approach to parametric study of machining parameters in determining the machinability of Inconel 718 with optimization technique" at the *International Conference on Robotics and Smart Manufacturing* held during 19-21 July 2018 organized by IIITDM Kancheepuram, Chennai, Tamilnadu.

Link: http://iiitdm.ac.in/rosma2018/

iv. Paper titled "Investigation of the process parameters in the machining of Inconel 718 with a carbide tool using taguchi methodology" at the *National conference on Mechanical Engineering and Emerging Technologies* held during 23-24 February 2018 organized by Faculty of Engineering, CHRIST (Deemed to be University), Bengaluru.

Link: https://christuniversity.in/NCMEET/

v. Paper titled "Parametric investigation on the tool wear while performing face milling on Inconel 718 using round insert" at the *International conference on Recent Trends in Advanced Material Processing* held during 20-21 March 2019

organized by Department of Mechanical Engineering, Chennai Institute of Technology, Chennai.

Link:http://www.chennaiinstituteoftechnology.com/upcoming-event/international-conference-on-recent-trends-in-advanced-material-processing-icrtamp-2019-is-organized-by-chennai-institute-of-technology-on-march-20-21-2019/

vi. Paper titled " An experimental analysis of machinability characteristics for investigating the machinability of Inconel 718" at the *International conference on Design, Materials, Cryogenics and Constructions* held during 28-29 March 2019 organized by School of Mechanical and Construction, VelTech Rangarajan Dr Sagunthala R & D Institute of Science and Technology, Chennai.

Link:http://www.knowafest.com/college-fests/events/2018/11/2807-international-conference-design-materials-cryogenics-constructions-icdmc-2019-vel-tech-rangarajan-dr-sagunthala-r-d-institute-science-technology-chennai

vii. Paper titled "Development and characterization of AlTiCrN coating on tungsten carbide insert" at the *International conference on Advancements in Mechanical Engineering* held during 10-11 April 2019 organized by Department of Mechanical Engineering, Jyothi Engineering College, Thrissur. **Link:** http://icame.jyothiengg.com/

viii. Paper titled "Influence of cryogenic treatment of cutting tool inserts on tool wear and surface roughness during milling of Inconel 718" at the *International conference on Advances in Materials research* held during 25-27 July 2019 organized by Department of Chemistry and Mechanical and Manufacturing Engineering in association with catalysis society of India-Bangalore Chapter, Ramaiah University of Applied Sciences, Bangalore.

Link: http://www.icamr-ruas.org/

3. POSTER PRESENTED IN INTERNATIONAL CONFERENCE

i. Paper titled "Experimental study of response parameters for improving the machinability characteristics of Inconel 718 using ceramic inserts" at the *International Conference on Advanced ceramics and nanomaterials for sustainable development* held during 19-21 September 2018, Faculty of Engineering, CHRIST (Deemed to be University), Bengaluru.

4. LIST OF WORKSHOPS ATTENDED

i. Participated in Author workshop on "How to write and publish scientific articles and manuscripts" held in 12 June 2018 jointly organized by Springer Nature and CHRIST (Deemed to be University).

ii. Participated in workshop on "Research methodology and IEEE Authorship Lab" held in 1-2 February 2019 organized by the Department of Computer Science (PG), Kristu Jayanti College in association with IEEE ComSoc, Bangalore.

iii. Participated in workshop on "Research and modern tools usage", held in 30-31 May 2019 organized by the Department of Mechanical and Automobile Engineering, CHRIST (Deemed to be University), Bangalore.

5. FUNDED PROJECT COMPLETED

i. Monograph (MNGDFE-1710): worked as a co-principal investigator in the project titled "Parametric optimization of hard machining of Inconel 718 using coated tools" funded by Centre for Research, CHRIST (Deemed to be University) in period of December 2017-May 2019.

6. CHAPTER PUBLICATION

i. **Rout I.S**., Pal Pandian P., G. Ravichandran, N. Santhosh, and Hebbar G. S, "Optimization of Cutting Parameters for Hard Machining on Inconel 718 Using Signal to Noise Ratio and Grey Relational Analysis," *Materials Physics and Chemistry: Applied Mathematics and Chemo-Mechanical Analysis*, Apple academic press, March 2020 (In Print).

Article

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A Review on Parametric Study of Hard Machining of Inconel 718 Using Coated Carbide Tool

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Super alloys sustain good strength at high temperature and pressure conditions. Such materials have high demand in aerospace industry, marine industry, and nuclear power plants. Superalloys are mainly nickel based alloys such as Inconel alloy 718 which is a high-strength, corrosion-resistant nickel chromium material. Because of such properties it becomes one of the hardest material to machine. The present study is to investigate the cutting conditions suitable for better machining, improving the surface roughness and minimizing tool wear. The different parameters required for better output are discussed. Even the lubrication aspect which plays a major role in providing better result is explained.

Keywords: Inconel 718, Coated Carbide Tool, Taguchi, Grey Relational Analysis, Machining Parameters.

1. INTRODUCTION

In the industries that require high performance alloys for aerospace, energy production, automotive and biomedical industries, it is important for mission-critical components to perform at aggressive working conditions. Some application in these industries require products to withstand high thermal and mechanical loading conditions for extensive amount of time. For such applications conventional materials like aluminium and steel may not perform and reliability and durability issues can arise. In these cases using more advanced material can be advantageous in long run and less costly too.[1] Inconel 718 is categorized as a nickel-based superalloy, which is extensively used in aerospace and energy industry, especially in the high temperature area of engine, because of their excellent mechanical resistance to high temperature and corrosion. Many previous investigations have reported that nickel-based superalloys are difficult to machine due to the following several reasons: (i) high hot hardness and strength causing deformation of the cutting tool; (ii) the rapid work hardening causing severe notch wear; (iii) presence of primary carbide particles encouraging abrasion tool wear; (iv) low thermal diffusivity leading to extremely high local temperature on cutting edge; (v) welding of the workpiece to the tool cutting edge forming unstable builtup edge (BUE) which deteriorate machined surface; and (vi) possible chemical reactions accelerating tool wear.[2] A number of different areas are being researched in order to counter the hard machining characteristics of nickel based alloys and achieve economy of the machining process. Some of these areas include development of the new tool and coating materials and methods, optimizing processes parameters, using different cooling and heating techniques, e.g., Laser assisted machining, plasma enhanced machining, cryogenically enhanced machining, hybrid machining, nitrogen cooling etc.[3] This study has been performed for finding out the various parameters dealt with machining of inconel 718 and the specific coated tool to be used to minimize tool wear and increase tool life.

2. TOOLING

Researchers have investigated the use of different tool materials, such as aluminum oxide base cermets, special carbide coating, whisker-reinforced ceramic, CBN, and others, to cut heat resistant super alloy. Uncoated carbide tools are used to machine nickel-based alloys at a cutting speed range of 25 m/min to 45 m/min, feed rates of 0.1 mm/rev to 0.2 mm/rev, and depth of cut of 1 mm to 1.5 mm for improved productivity. Carbides are most widely used as cutting tool material to machine Inconel

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718 at slow speeds. Inconel 718, a heat resistant super alloy material, is widely used in aerospace, nuclear, and gas turbine industries due to its excellent characteristics, namely, high strength-weight ratio at elevated temperature, exceptional corrosion resistance, and longer service life.[4] Cubic boron nitride (CBN) has received a great deal of attention as a material for cutting tools. CBN has high thermal conductivity, high hot hardness, and good thermal stability, and it is one of the hardest materials known after diamond. CBN cutting tools are already used, especially in the cutting of ferrous materials, and are also considered to be a major candidate for Inconel 718 cutting. However, the performances of CBN tools are still insufficient in practical use in light of their extremely high fabrication cost, about ten times the price of conventional carbide tools or ceramic tools.[5] In the present study coated carbide tool is to be used to reduce tool wear and improve surface roughness. As Inconel is flexible and has a high memory, meaning it will 'give' somewhat when subjected to the forces of a cutting tool. So, the longer the contact time between the cutter relief and material, the higher the abrasive wear on the tool and the shorter its working life. To further reduce the friction between cutter and Inconel, a coating has to be incorporated in the tool.

Barthelma et al.[6] in 2016 investigated PVD-hard coatings with specific requirements. Relevant properties are the thermal and mechanical stability, the thermal protection of the substrate, the reduced friction and a very good coating adhesion. Process simulations were used to calculate process conditions like cutting temperatures and forces and to determine cutting strategies with reduced load. Hard coating systems and process simulation were used to optimize the milling of the nickel based alloy Inconel 718 with carbide ball nose end mills. To achieve the objectives of an improved machining process, different boundary conditions and processes were taking into account regarding the following procedure of investigations:[6]

- Determination of process characteristic
- Influence of the substrate material
- Development of PVD hard coating systems
- Substrate-pre and coating post-treatment
- Application test.

3. MACHINING PARAMETERS

Machining parameters and tool geometry are important factors that affect machinability properties. A machinability model may be defined as a scheme of the functional relationship between input parameters (cutting speed, feed, and depth of cut) and output responses in the machining process. In developing a mathematical model, experiments involving the tool and work materials must be conducted. Response data are obtained from the experimental work, by keeping cutting speed, feed, and depth of cut as the function of the machining process.[4]

When the cutting speed is about 30 m/min the cutting temperature can exceed 1100 °C. This can lead to diffusion of carbide particles and to the weakening of the bonding strength between carbides and binder. Materials such as Inconel 718 have also high strength and hardness which leads to high flow stress of about 1–3 GPa on the tool when these materials are machined. Notch wear at the depth of cut is observed due to the hardened layer, which arises due to the extreme self-hardening of these materials. Therefore it is necessary to select suitable cutting conditions with respect to the cutting material. The coatings are beneficial due to lower friction and higher thermal stability of the cutting tool. The recommended cutting speed is in tens of m/min when coated carbide tools are used. The feed rate must be selected appropriately in view of the fact that when the feed rate is too low, the time of friction on the flank of the tool is longer. Basically the increase in the time delay before opening the chip/tool interface leads to higher thermal stress.[7]

4. LUBRICATION

During the last decades, there have been major efforts in developing and implementing more effective cooling/lubrication methods in machining of hard-to-cut aerospace alloys, including Inconel 718. The most common among these methods were high pressure coolant applications, minimum quantity lubrication (MQL), and more recently, cryogenic cooling. These methods were proposed for improving the machining performance of Inconel 718 alloys and reducing the production costs, and to make the processes more environmentally friendly. Since cryogenic cooling is proposed as an alternative approach to offer cooling as well as lubrication, it should be tested and compared with MQL in machining of different materials. No research has been done in the systematic study of comparing cryogenic cooling with MQL and dry cutting in machining of Inconel 718 alloy, particularly considering the machining performance such as cutting forces, progressive tool wear, cutting temperature, chip morphology, etc.[8]

Colak investigated in 2012 application of high pressure cooling/lubrication fluid to the tool-chip interface and found it decreases cutting force components on account of the mechanical effect of high pressure coolant. High pressure cooling improves tool life and provides desirable chip breakability, which tends to improve the quality of machined surfaces. Cutting tool wear, especially flank face wear, reduces with applying high pressure coolant to the tool-chip interface. The high pressure coolant technique supports the sustainability manufacturing, especially hard-to-cut materials, by increasing tool life and reducing the cutting forces resulting in higher productivity and lower energy consumption.[9]

Uma et al.[10] investigated in 2016 surface quality of machined work material during WS_2 solid lubricant

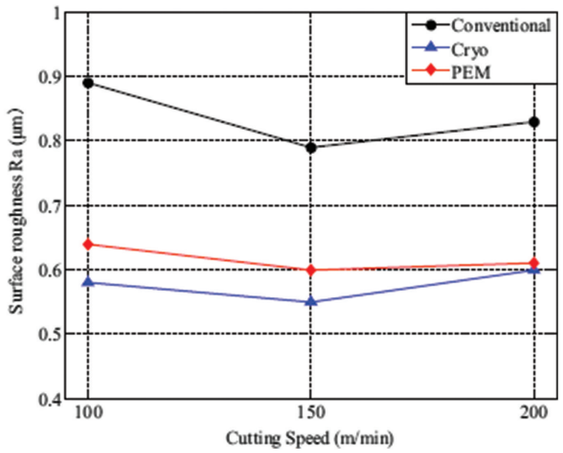

Figure 1. Surface roughness versus cutting speed.

assisted MQL machining showed a much improvement on the finish quality of work material by on average about 35% when compared to MQL machining alone.[10]

The Figure 1 shows the average workpiece surface roughness data versus cutting speeds with dry, liquid nitrogen cryogenic cooling, and PEM cutting conditions. The results indicate that the cryogenic cooling-assisted technology can obtain the best surface roughness, followed by the PEM condition, and finally the dry cutting condition. Better surface roughness is obtained with cryogenic cooling condition compared to the conventional cutting with ceramic cutting inserts. This may be attributed to the high liquid jet stream that will blow off the chips which can damage the surface. It has also been found that the surface roughness decreases with an increase in the cutting speed under all three different cutting conditions, and the most desired surface roughness has been obtained at the cutting of 150 m/min.[11]

Park et al.[12] studied the performance of tool wear in both dry and wet conditions using different lubricants. He experimentally proved that cryogenic treated insert in dry machining showed superior performance with only a small fraction of adhesion on the cutting surface, and wet machining also showed steady tool wear without any thermal fracture. From a scoring mark on the rake face it can be inferred that the dominant wear mechanism is abrasion. Unexpectedly, both MQL and Nano-MQL showed worst tool wear and chipping at the cutting edge while dry showed stable crater wear with small chipping at the notch area. Again, the cryogenic treated insert shows the least tool wear by cryogenic hardening of the cutting tool that improves the wear resistance. The wear volume of the dry machining was slightly smaller than that of the wet machining.[12]

5. OPTIMIZATION METHODOLOGY

The optimization method presented in this study is an experimental process called the Taguchi optimization method. Taguchi optimization, developed by Dr. Genichi Taguchi, is a set of methodologies in which the inherent variability of materials and manufacturing processes has been taken into account at the design stage. In Taguchi optimization, the multiple factors can be considered at once. Moreover, it seeks nominal design points that are insensitive to variations in production and user environments to improve the yield in manufacturing and the reliability in performance of a product. The complete procedure in Taguchi optimization method is consisting of three stages: system design, parameter design, and tolerance design. However, the parameter design is the most important stage. It has been widely applied in the USA and Japan with great success for optimizing industrial/production processes. The most important step in the parameter design is the selection of control factors. As many factors as possible should be included, so that it would be possible to identify nonsignificant variables at the earliest opportunity. The steps included in the parameter design of an experiment are: selecting the orthogonal array (OA) according to the numbers of controllable factors, running experiments based on the OA, analyzing data, identifying the optimum condition, and conducting confirmation runs with the optimal levels of all the parameters. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. The methodology of Taguchi for three factors at three levels is used for the implementation of the plan of experiments. The degrees of freedom required for the study is six and Taguchi's L9 orthogonal array is used to define the 9 trial conditions.[13] In this research, the Taguchi optimization method is applied to identify the optimal control factors combination that yield the lowest cutting force and surface roughness value (Ra). To achieve this goal, the following items will be investigated:[14]

- The relationship between the controllable factors (feed rate, spindle speed, and dept of cut) and the response factor (surface roughness, cutting force and material removal rate)
- What are the suitable conditions of the controllable factors for minimizing surface roughness?

Maiyar et al.[15] determined the optimal parameters through Grey Relational Analysis (GRA). In the GRA, data pre-processing is first performed in order to normalize the raw data for the analysis. In the study, a linear normalization of the experimental results for surface roughness and material removal rate were performed in the range between zero and one, which is also called grey relational generating. The normalized experimental results x_{ij} can be expressed as:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \quad (1)$$

where y_{ij} for the ith experimental results in the jth experiment.

Next, the grey relational coefficient is calculated to express the relationship between the ideal (best) and the actual normalized experimental results. The grey relational coefficient ξ_{ij} can be expressed as:

$$\xi_{ij} = \frac{\min_i \min_j |x_i^0 - x_{ij}| + \xi \max_i \max_j |x_i^0 - x_{ij}|}{|x_i^0 - x_{ij}| + \xi \max_i \max_j |x_i^0 - x_{ij}|} \quad (2)$$

Where x_i^0 is the ideal normalized results for the ith performance characteristics and is the distinguishing coefficient which is defined in the range $0 \leq \xi \leq 1$. In the study the value of ξ is assumed as 0.5. Then, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristics. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, that is:

$$\gamma_j = \frac{1}{m} \sum_{i=1}^{m} \xi_{ij} \quad (3)$$

Where γ_j is the grey relational grade for the jth experiment and m is the number of performance characteristics.

Higher the grey relational grade better is the product quality. Therefore, on the basis of grey relational grade, the factor effect can be estimated and the optimal level for each controllable factor can also be determined.[15]

6. RESULT PREDICTION

Thirumalai et al.[4] determined the attributes surface roughness (Ra), flank wear (Vb), tool life (TL), cutting force (Fc), power consumption (P), and MRR (MRR). Attributes Ra, Vb, F, and P are non-beneficial (minimum values), whereas attributes TL and material removal rate (MRR) are beneficial (maximum values). These six objective functions with six constraints were considered. All six objective functions were considered equally important, which added complexity to the selection of machining parameters.[4]

Kaynak investigated that selected cutting parameters and cooling/lubricating conditions did not improve chip breakability, while increased cutting speed profoundly reduced helical chip diameter. Cryogenic cooling generated thicker chips that were segmented and had bigger pitch than chips generated in dry and MQL conditions. Surface quality was improved by using cooling/lubricating. At higher cutting speeds, cryogenic machining generated the best surface quality attributed to less tool wear and less thermal distortion. At lower cutting speed, some surface defects on the surface of dry machined sample were observed. Considering the obtained results, using cryogenic cooling at higher cutting speed in machining of Inconel 718 is highly recommended.[8]

Halil Cahskan et al.[16] investigated the influence of coating, cutting speed, feed rate and depth of cut on the cutting forces (F_x, F_y, F_z) and Ra in hard milling of AISI O_2 (~61 HRC) cold work tool steel were experimentally investigated based on RSM. The influence of nanolayer AlTiN/TiN, commercial TiN/TiAlN and multilayer nanocomposite TiAlSiN/TiSiN/TiAlN coated tools on Ra were compared. The experiments were conducted based on 313 factorial design by response surface methodology, and response surface equations of cutting forces and surface roughness were obtained. In addition, the cutting forces obtained with the coated and uncoated tools were compared. The results showed that the interaction of coating type and depth of cut affects surface roughness.[16]

Ma et al.[17] studied the optimum range of spindle speed in the high-speed milling of Inconel 718 in which curved surface is obtained, and the feed per tooth and the cutting depth are analyzed based on cutting force as well. An interesting phenomenon can be found that in the spindle speed range from 4,000 to 4,500 rpm, the cutting force is relatively smaller and the change of cutting force is smoother for different points with different geometric features. So, the spindle speed can be selected optimally in this range for the machining of the Inconel 718 parts with curved surface. It is evident that the effect of the feed per tooth on the change of cutting force is little in high-speed milling of Inconel 718 parts with curved surface, and the feed per tooth can be selected according to the processing requirement. With the increase of the cutting depth, the cutting forces of all the seven points grow obviously. And the change of cutting forces at a certain cutting depth becomes sharp as the different features for the seven points. So, the cutting depth should be small for the small fluctuation of cutting force.[17]

Fernandez et al.[18] compared different types of cooling and cutting fluids. He found that cryogenic machining shows the lowest rate of tool wear increase compared to the other cooling systems, so the superior cooling capacity of this technique is evidenced. Cryogenic machining results in less tool wear than emulsion based, cold air and dry machining, having a tool life increase of 34,6%, 55,9% and 75,4% respectively. Therefore this is a more efficient and not harmful to the environment process. The cold air assisted machining, although being an economic solution, is not able to match the performance of conventional methods and therefore is not a valid alternative. Thus, the main conclusion of this work is that cryogenic fluids are a potentially valid way to improve the cutting process of advanced materials in an ecologically responsible way.[18]

Mohamed Handawi Saad Elmunafi et al.[19] found that tool life decreases with increase in both cutting speed and feed. Coated carbide cutting tools was able to perform at high hardness of 48 HRC in range of cutting parameters selected. Maximum tool life of 33.7 min was obtained at low combination of cutting speed and feed whereas the shortest tool life was 1.5 min at high combination of cutting speed and feed rate. This significant result of tool life when turning hardened steel (AISI 4340) of 46 HRC with

speed of up to 120 m/min and feed of 0.1 mm/rev under MQL technique. The cutting fluid with MQL technique was able to penetrate deep into the tool-chip and tool-workpiece interface which supports coated carbide tool to perform better at high cutting condition and resulted in longer tool life.[19]

Aziz Ul Hassan Mohsan et al.[20] investigated the progress towards the improvement in surface integrity of Inconel 718 has been reviewed in his paper. Good surface integrity can be achieved during the machining process by making proper selection of machining parameters (cutting tool, cutting speed, feed rate, depth of cut, etc.) and cooling conditions (coolant type, coolant pressure, and coolant direction) which can maintain a suitable compromise between the resulting surface roughness, substructure damage, and residual stresses. Among the available machining processes, dry machining does not seem to be beneficial for the machining of Inconel 718. Flood cooling during the machining of Inconel 718 provides better cooling effect which results in a machined component with lower degrees of surface roughness, subsurface damage, and tensile residual stresses under lower cutting speeds. However the beneficial effect of flood cooling is not so obvious at higher cutting speeds because of the bubble barrier or seizure effect that hinders heat transfer between the coolant and the workpiece. The non-applicability of higher cutting speeds in flood cooling conditions does not make the flood cooling favorable for industrial machining of Inconel 718 on the grounds of productivity.[20]

7. CONCLUSION

Machinability of nickel based super-alloys is extremely poor, mainly due to their low thermal conductivity, build up edge and self-hardening, which leads to high dynamic cutting forces. They are difficult to machine because, high shear strength, work hardening, precipitation hardening. High abrasive particles in its microstructure and tendency forming chip to weld to tool and form built up edge (BUE) make it more difficult to machine. After the literature review, it has been found that the machining parameters considered are cutting speed, feed, and depth. Surface roughness, flank wear, cutting force, power, tool life, and material removal rate are considered as responses in machining Inconel 718. Taguchi methodology and grey relational analysis will help to find optimal conditions for better machining and providing the best suited result for better output.

8. SCOPE FOR FUTURE WORK

Since industries are in need of material that can replace the light weighted material such as aluminium and steel under heavy load and can be used under heavy loading conditions. There is a way to reach their prime motives of supplying materials which are needed and hence inconel alloy which is a prime material to resolve their issues and fulfill their needs. Extensive findings are going on to machine this hard to cut material and an investigative approach to this field can pave a solution to this huge innovative material. Therefore CNC milling is one way to improve the machining of this inconel alloy due to its high speed accuracy, close dimensional tolerances, better surface finish and good lubrication for the cutting tool. Hence the study is a landmark to show that some surfaces can be machined to a level even though they are hard to cut materials. The idea is to investigate how far the surface can be machined and upto what depth keeping in mind the machining parameters and lubrication properties.

References and Notes

1. D. Ulutan, A. Pleta, A. Henderson, and L. Mears, *Procedia Manufacturing* 1, 522 **(2015)**.
2. J. Zhou, V. Bushlya, P. Avdovic, and P. E. Stahl, *International Journal of Advance Manufacturing Technology* 58, 141 **(2012)**.
3. W. Akhtar, J. Sun, P. Sun, W. Chen, and Z. Saleem, *Front. Mech. Engg.* 9, 106 **(2014)**.
4. R. Thirumalai and J. S. Senthilkumaar, *Journal of Mechanical Science and Technology* 27, 1109 **(2013)**.
5. T. Sugihara, S. Takemura, and T. Enomoto, *International Journal of Advance Manufacturing Technology* 87, 9 **(2016)**.
6. F. Barthelma, H. Frank, M. Schiffler, and A. Bartsch, *Procedia CIRP* 46, 294 **(2016)**.
7. V. Schornik, M. Zetek, and M. Dana, *Procedia Engineering* 100, 1262 **(2015)**.
8. Y. Kaynak, *International Journal of Advance Manufacturing Technology* 72, 919 **(2014)**.
9. O. Colak, *Journal of Mechanical Engineering* 58, 683 **(2012)**.
10. U. M. R. Paturi, Y. R. Maddu, R. R. Maruri, S. K. R. Narala, *Procedia CIRP* 40, 138 **(2016)**.
11. K. Zhuang, X. Zhang, D. Zhu, and H. Ding, *International Journal of Advance Manufacturing Technology* 80, 1815 **(2015)**.
12. K. H. Park, G. D. Yang, and D. Y. Lee, *International Journal of Precision Engineering and Manufacturing* 16, 1639 **(2015)**.
13. G. Taguchi, Introduction to Quality Engineering, Asian Productivity Organization, Tokyo **(1990)**.
14. A. Hamdan, A. A. D. Sarhan, and Md. Hamdi, *International Journal of Advance Manufacturing Technology* 58, 81 **(2012)**.
15. L. M. Maiyar, R. Ramanujam, K. Venkatesan, and J. Jerald, *Procedia Engineering* 64, 1276 **(2013)**.
16. H. Kahskan, C. Kurbanoglu, P. Panjan, and D. Kramar, *International Journal of Advance Manufacturing Technology* 66, 883 **(2013)**.
17. J. Ma, F. Wang, Z. Jia, Q. Xu, and Y. Yang, *International Journal of Advance Manufacturing Technology* 75, 269 **(2014)**.
18. D. Fernandez, V. G. Navas, A. Sanda, and I. Bengoetxea, *MM Science Journal* 514, 506 **(2014)**.
19. M. H. S. Elmunafi, M. Y. Noordin, and D. Kurniawan, *Procedia Manufacturing* 2, 563 **(2015)**.
20. A. U. H. Mohsan, Z. Liu, and G. K. Padhy, *International Journal of Advance Manufacturing Technology* 1 **(2016)**.

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Selection of cutting parameters for the machinability of Inconel 718 using Grey Relational Analysis

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Abstract. Inconel 718 is considered to be most difficult to machine superalloy because of its high shear strength, work hardening and precipitation hardening. Abrasive particles which are in microstructure have tendency have forming chip to be welded to tool and form built up edge (BUE) making it more difficult to machine. Friction between tool and material and its low thermal conductivity results in high temperature generation. Certain tools such as Ceramics are present which machine this material at prime cutting conditions. This paper addresses the cutting parameters needed most for providing low surface roughness

1 Introduction

Inconel 718 is one such nickel based alloy which is characterized by high strength, good oxidation, fatigue and creep resistance at high temperature. These properties are of great interest in domains such as the ones cited before, but result in an added difficulty in machining. Its high strength, hardening tendency and low thermal conductivity results in cutting processes including high forces and temperatures points. The machining of these materials, accordingly, is associated with low machinability and productivity, where tool wear, finishing accuracy and/or high production costs greatly limit the efficiency.

Ceramics tool is one of the cutting tool that is being used for cutting this hard material as it can operate at high speeds and depth of cut required to machine generate suficient heat to enable machining. These cutting tools have tendence to operate at high temperature and hard machinability environments which provide a better surface to the material.

CNC milling machine is one of the advanced machines that is being used for the machinability of Inconel 718 which can operate at elevated temperature conditions providing greater accuracy to the toola nd better dimensional tolerance features to the workpiece. These machines provide high productivity and can find a space in machining field for better finishing and quality of substrates being used.

2 Machining Parameters

2.1 Cutting speed: It is the relative velocity between the cutting tool and the surface of the work piece it is operating on. The unit of cutting velocity is revolutions per minute (rpm).

2.2 Feed Rate: It is the relative velocity at which the cutter is advanced along the work piece. The unit of feed rate is millimeters per min (mm/min).

2.3 Depth of Cut: The thickness that is removed as a work piece is being machined. The unit of depth of cut is millimeters (mm).

2.4 Surface Roughness: Defects may occur either in material surfaces during processing or after use, and defect analysis of in essential for providing the information to improve effectiveness, efficiency and durability of surfaces. Surface roughness also known as surface profile (Ra) is a measurement of surface finish. It is a topography at a scale that might be consider "texture" on the surface. Surface roughness is a quantitative calculation of the relative roughness of a linear profile area expressed as a single numeric parameter (Ra).

3 Experimental set-up

3.1 Cnc Milling Machine

The experimental study was carried out in wet cutting conditions on a high-speed milling machine equipped with a maximum spindle speed of 1800 rpm, feed rate of 10m/min and a 25-kw drive motor. The below figure shows the work bench of a cnc machine.

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Fig 1 Working environment of CNC milling machine

3.2 Workpiece

The work piece material used was Inconel 718 in the form of a 75mm (length), 50 mm (width) and 40 mm (height) block. To provide maximum rigidity, the work piece material is mounted onto the machine table.

Fig 2 Workpiece sample of Inconel 718

3.3 Ceramic Tool Insert

The tool used for end milling operation is Ceramic tool. The grade of the ceramic tool is AS20. The coating layer on the ceramic tool is Si_3N_4 . The ISO range of the ceramic tool is (S05-S20).

Fig 3 Sample of Tool Insert

3.4 Surface profilometer

Surface profilometer is the measuring instrument used to measure the roughness of a surface and gives the result as the average distance between the two peaks of the regular profile. The equipment consists of measuring tip, cantilever transducer and a control system to plot the profile of surface in 2D graph and calculate the mean value of it. The setup is done in such a way that the tip is just placed on the surface of the specimen (which is indicated by the blue line on the screen) and the firm placement of the body. By pressing the start button, the measuring tip starts to travel finite pre-defined distance (20mm, may differ with settings) on the irregular profile of the surface and comes back to the original position. The cantilever type transducer provides free oscillation movement to the tip while the instrument body is firmly fixed. This movement is converted into digital data directly by the transducer and profile is plotted. Based on the plotted graph the profilometer calculates the mean value and the result is obtained.

Fig 4 Surface Profilometer

3.5 Stop watch

Stop watch is a time piece designed to measure the amount of time taken to do a particular task. It measures the time from when it is activated to whenever it is deactivated. The stop watch is started and stopped manually.

Fig 5 Stop Watch

3.6 Tool maker's Microscope

Tool maker's microscope is used for the measuring very small distances on objects like peak distance of the bolt treads, gear tooth, etc. The specimen is placed on the glass plate (stage glass) where the source of light is fixed underneath, and the plate is connected to the guiding screw with handle for the adjustments.The image view from the scope has thin line of cross and the center of the cross is to be set on the starting point of the measurement. For the tool wear measurement, the end line of the grey surface shown on the microscope is set as the starting point and the distance to the end of the circumference of the tool insert is measured by rotating vertical handle.

Fig 6 Mitutoyo Tool Maker's Microscope

4 Methodology

4.1 L9 Array

Thisexperiment was done using Taguchi orthogonal array technique. Taguchi method uses a special design of orthogonal arrays to study the entire parameters with a small number of experiments. Taguchi's L9 orthogonal array is used to define the 9 trial conditions. The process parameters are listed in below table.

Table 1. Process parameters and their levels

Parameter	Unit	Symbol	Level 1	Level 2	Level 3
Cutting Speed (v)	*rpm*	A	400	600	800
Feed Rate (f)	*mm/min*	B	5	10	15
Depth of cut (d)	*mm*	C	0.2	0.4	0.6

The experimental layout using L9 orthogonal array is shown . Nine experimental runs are carried out using different combinations of the process parameters as mentioned. Surface Roughness for all the different combinations were found. The different experimental values of the output parameters are shown in Table 2.

Table 2. Experimental layout of L9 array

Experiment No	Process Parameter			Average
	A	B	C	X
1	1	1	1	1.038
2	1	2	2	0.607
3	1	3	3	0.943
4	2	1	2	0.736
5	2	2	3	1.532
6	2	3	1	0.471
7	3	1	3	1.710
8	3	2	1	0.632
9	3	3	2	0.569

4.2 Setting up the Eigen-value matrix, input original data

$$X = \begin{bmatrix} X_1(1) & X_1(2) & X_1(3)\ldots\ldots & X_1(n) \\ X_2(1) & X_2(2) & X_2(3)\ldots\ldots & X_2(n) \\ X_3(1) & X_3(2) & X_3(3)\ldots\ldots & X_3(n) \\ \vdots & \vdots & \vdots & \vdots \\ X_m(1) & X_m(2) & X_m(3)\ldots\ldots & X_m(n) \end{bmatrix}$$

Where

m –no. of listed experimental runs
n –no. of influence factors
$X_m(n)$ –corresponding value of the m experimental run and n influence factor
An Eigen value matrix is setup according to the experimental run and the corresponding influence factors. In the corresponding values of the matrix, m represents the number of listed experimental runs and n represents the number of influence factors.
For example:
33
• $X_1(1)$ means that the corresponding value represents the first experimental run and the first influence factor.
• $X_6(3)$ means that the corresponding value represents the sixth experimental run and the third influence factor.

Table 3. Process parameters and their Original data of the influence factors

Experimental Run	Surface Roughness (μm)
1	1.038
2	0.607
3	0.943
4	0.736
5	1.532
6	0.471
7	1.710
8	0.632
9	0.569

4.3 Standardized data transformation using formulas

After the first step all the values are subjected to a transformation process. This transformation process is based on the influence factors.

Influence factors refer to the output parameters of the experiment. The influence factors is surface roughness.

Defect-type Factor: The smaller the better

$$X_m(n) = \frac{max[X_m(n)] - X_m(n)}{max[X_m(n)] - min[X_m(n)]} \quad (1)$$

Medium-type factors are the influence factors that we tend to be near a certain standard value. Thus we use the medium-type factor transformation formula when we want values to be near to a standard reference value. The maximum value in each column is denoted by max[X_m(n)] and the minimum value in each column is denoted by min[X_m(n)].

4.4 Calculation of Grey Relational Degree

4.1.1 Selection of the best value for each influence factor

The best value for each influence factor is selected Surface Roughness should be less. Hence the least value of Surface Roughness is selected and chosen as the referential series for further calculation.

Table 4. The referential series and standardized data

Experimental Run	Surface Roughness (μm)
X0	0.144
1	0.890
2	0.619
3	0.786
4	0.144
5	1.000
6	0.000
7	0.870
8	0.9217
9	0.542

4.1.2. Getting the absolute difference of compared series and referential series

The difference between the obtained standardized data and the referential series is found. This is done to indicate the relational degree between 2 measurement sequences.

4.1.3. Find out the minimum and maximum

The maximum and minimum value of each influence factor is found. The maximum value is denoted as max[X_m(n)] and the minimum value is denoted as X_m(n).

4.1.4. Choose the constant p

The constant p is known as the distinguishing co-efficient. The distinguishing co-efficient p is between 0 and 1. Generally, p is set to 0.5.

4.1.5.Calculation of relational co-efficient and relational degree using formula.

For every value of surface roughness and material removal rate, relational co-efficient and relational degree has to be found out. Relational coefficient can be calculated by,

$$\tau_m(n) = \frac{\Delta min + p\Delta max}{\Delta X_m(n) + p\Delta max} \quad (2)$$

Relational degree can be calculated by,

$$r_m(n) = \Sigma\,(w\tau_m) \quad (3)$$

Table 5. The relational degree and ranking

	Surface Roughness (μm)	Relational Degree	Rank
w	0.9		
τ1	0.4872	0.4385	4
τ2	0.6334	0.5701	7
τ3	0.5346	0.4811	6
τ4	1.3364	1.2028	1
τ5	0.4455	0.4001	2
τ6	1.0000	0.9000	9
τ7	0.4965	0.4468	5
τ8	0.4747	0.4272	3
τ9	0.6925	0.6232	8

5 Results and discussion

At the end of Grey Relational Analysis (GRA), the experimental run or trial with the highest value gets the first rank. The ranks of all the experimental runs are mentioned in below table:

Table 6. The ranking of the experimental runs

Rank	1	2	3	4	5	6	7	8	9
Experimental Run	4	5	8	1	7	3	2	9	6

After getting the results, graphs for surface roughness for different cutting speeds were plotted.

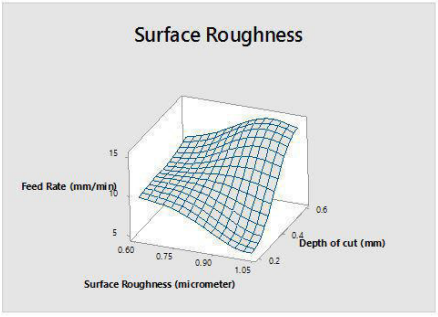

Fig 7 Surface Roughness for Spindle Speed 400 rpm

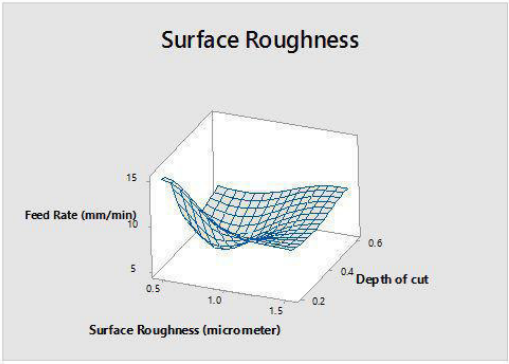

Fig 8 Surface Roughness for Spindle Speed 600 rpm

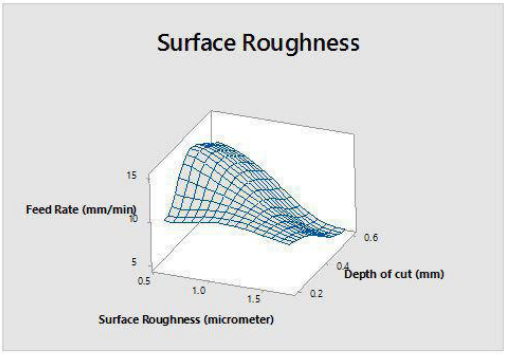

Fig 9 Surface Roughness for Spindle Speed 800 rpm

6 Conclusion

The optimal conditions for minimal surface roughness in improving the surface is found at cutting speed of 600 rpm, feed rate of 5 mm/min and depth of cut 0.4 mm. Grey relational analysis is depicting as an effective tool in determing the machinability of inconel 718 using ceramic tool insert. The hardened alloy can be machined at this environment conditions for providing higher surface finish and cutting conditions can be improved in wet machining.

References

[1] A. Xavior, Manohar, Jeyapandiarajan and P. M. Madhukar, *Tool wear assessment during machining of inconel 718*, 13th Global Congress on Manufacturing and Management, **174**, pp. 1000-1008 (2017).

[2] K. Venkatesan, Journal of Advanced Research, **8**, pp. 407-423 (2017).

[3] W. Li, Y. Guo, M. Barkey and J. Jordon, *Effect Tool Wear during End Milling on the Surface Integrity and Fatigue Life of Inconel 718*, 6th CIRP International Conference on High Performance Cutting, **14**, pp. 546-551 (2014).

[4] D. D'Addona, S. J. Raykar and M. M. Narke, *High speed machining of Inconel 718: tool wear and surface roughness analysis*, 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering, **62**, pp. 269-274 (2017).

[5] M. P´erez, C. Rodrıguez and F. J. Belzunce, *The use of cryogenic thermal treatments to increase the fracture toughness of a hot work tool steel used to make forging dies*, 20th European Conference on Fracture, **3**, pp. 604-609 (2014).

[6] S. A. Chopra and V. G. Sargade, *Metallurgy behind the Cryogenic Treatment of Cutting Tools: An Overview*, 4th International Conference on Materials Processing and Characterization, **2**, pp. 1814-1824 (2015).

[7] A.Shokrani, V. Dhokia and S. T. Newman, *Hybrid cooling and lubricating technology for CNC milling of Inconel 718 nickel alloy*, 27th International Conference on Flexible Automation and Intelligent Manufacturing, **11**, pp. 625-632 (2017).

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Parametric investigation of machining parameters in determining the machinability of Inconel 718 using taguchi technique and grey relational analysis

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Abstract

High performance super alloys are most in demand for mission critical components to perform in aggressive working conditions. These alloys withstand high thermal fatigue conditions and provide better stability to machine components in aerospace, marine, energy production, biomechanical, automotive industries. Inconel 718 is one such alloy extensively used in this loading conditions due to high thermal corrosion, chemical stability, mechanical friction and high strength. Cutting tools such as tungsten carbide are being used to machine such hard to cut materials. This paper discusses the cutting parameters needed for the machining of Inconel 718 to produce low tool wear and minimum surface roughness.

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*Keywords:*Inconel 718, tunsten carbide insert, CNC milling, ANOVA, GRA

Nomenclature

v	Cutting speed
d	Depth of cut
f	Feed rate
$X_m(n)$	Defect type factor
τ_m (n)	Relational coefficient
$r_m(n)$	Relational degree
ω	percentage of a particular factor influencing the experiment. The sum of ω is always 100%.

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1. Introduction

Hard machining is the concept of machining materials whose hardness value is above 45 HRC and primarily ranges from 45-68 HRC. These materials are being used in components which need high tensile strength, rigidity, high fatigue loading, high thermal shock resistance, high chemical stability, high resistance to corrosion. The machining of these materials is associated with high tool wear, low surface roughness, low cost, efficiency, low finishining and poor machinability [5]. However some tools have been developed to overcome these conditions and provide better features and characteristice to the machining parameters.

1.1. Inconel 718

It is a nickel based super alloy with excellent high strength and mechanical properties at elevated temperatures and cryogenic temperatures. It can be readily worked and age hardened. Its temperature at high strength ranges from -253°C to 705°C. It is used in the field of cryogenic tanks, gas turbine componets, high pressure vessels, rocket jet fuel engines, submarines, ships, heavy framed tanks, etc. The chemical composition of Inconel 718 is as follows:

Table 1: Chemical Composition of Inconel 718 (wt%) [1]

Elements	C	Mn	Ti	Si	Al	Co	Mb	Cb	Fe	Cr	Ni
Percentage	0.08	0.35	0.6	0.35	0.8	1.0	3.0	5.0	17.0	19.0	52.82

A workpiece sample of Inconel 718 has been used in the form of a 75mm (length), 60mm (width) and 50mm (height) block.

Fig 1 Sample of workpiece (Inconel 718)

1.2. Tungsten Carbide Insert

It is a small round insert of RYMX 1004-ML of grade TT3540. It is used for end milling operation. It is coated with Si_3N_4. A specific type of tool shank is being used to hold this insert for milling operation. The insert is capable of withstanding cutting tool forces being generated during machining of superalloy Inconel 718. It also provides better surface allignments and tool stability while in operation.

Fig 2 Tungsten carbide Insert

Fig 3 Tool shank

1.3. Tool Wear

It is one of the predominant factors in defining the input parameters responsible for providing better finish on the surface of the workpiece [1]. It is caused due to the high temperature zone between the tool and the chip. There are basically two types of wear: flank wear and crater wear. Both are caused due to wear mechanisms which are categorised as abrasion, adhesion, diffusion, tribomechanical wear, diffusion and fatigue [2]. These mechanisms

are the influencing mechanisms for causing wear in the tool. So the uttermost care has to be taken during the machinability of Inconel 718 using tungsten carbide as the tool.

1.4. Surface Roughness

It is a topography on the surface that is measured within the peak values of the surface (Ra). It determines the surface texture after machining and the accuracy of the tool for the material removal. It is also the measurement of the surface finish and how the surface is aligned after the material has been removed [3]. It is one of the important response parameter that has to be determined after the cutting parameters have been fed into the system to know the cutting tool has better machining features over the Inconel 718.

1.5. CNC Milling Machine

It is one of the most advanced part programming machines existing. Besides providing high accuracy and dimensional tolerances, it can operate at high speed providing better finish on the workpieces. Specifications of the CNC machine:

CNC System: BOSCH MTX Micro-Milling
No of Axis: 3
x-axis stroke: 210mm
y-axis stroke: 210mm
z-axis stroke: 245mm
Spindle Nose Taper: B40
Tool Clamping: Hydro Pneumatic
Spindle Speed: 50 - 4000rpm
Spindle Power: 12NM (2.5 KW)
Table Working Area: 160x230mm
Table height from floor:1000 mm
Rapid rate: 10 m/min
Coolant tank: 50 ltrs
Lubrication Tank: 3 ltrs
Power Supply: 3 Phase, 415V, 50Hz, 8KW

Fig 4 Vertical CNC Milling Machine

1.6. ANOVA (Analysis of variance)

It is an optimization method of comparing the means of two or more groups. It shows the correlation between the groups and significant effect of contribution. If the p-value for the ANOVA results is less than what is chosen significance level (usually 0.05), there is evidence that at least one mean is different. If the p-value is not significant, then analysis is over and conclusion is drawn that there is no difference between any pair of means. The groups are the control parameters cutting speed, feed rate and depth of cut along with the response variables surface roughness and tool wear.

1.7. GRA (Grey Relational Analysis)

It is one of the effective means of determining the range of sequence is large or standard value is enormous. However, if the standard values and goals are different, grey relational analysis produces incorrect results. Therefore, one has to pre-process the data in order to implement the analysis and draw the conclusion for finding the optimum output. This analysis finds out the corelation between two factors and decides the distances between

them to carry out the experimental run. Hence, it proves as an effective analysis technique in investigating the control parameters required for producing the response variables.

2. Experimental analysis

2.1. Experimental Layout

An experimental run has been carried out using L9 orthogonal array. Nine experimental runs have been carried out and the control factors and process variables are shown in the table 2.

Table 2 Control factors and their levels for the experiment

Parameter	Unit	Symbol	Level 1	Level 2	Level 3
Cutting Speed	rpm	v	500	600	700
Feed Rate	mm/min	f	10	15	20
Depth of cut	mm	d	0.2	0.4	0.6

The experiments has been done in CNC vertical milling machine in which tungsten carbide insert has been used to machine Inconel 718 under this control factors producing the response variables surface roughness and tool wear.

Table 3 Experimentation with the response variables and S/N ratio

	Control Factors			Response Variables		S/N ratio	
S.No	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)	Tool wear (mm)	Surface Roughness (µm)	Tool wear (mm)
1	500	10	0.2	0.78	0.050	2.158	26.021
2	500	15	0.4	0.62	0.025	4.152	32.041
3	500	20	0.6	0.44	0.057	7.131	24.882
4	600	10	0.4	0.89	0.040	1.012	27.959
5	600	15	0.6	0.78	0.148	2.158	16.595
6	600	20	0.2	0.36	0.050	8.874	26.025
7	700	10	0.6	0.54	0.405	5.352	7.840
8	700	15	0.2	0.27	0.050	11.373	26.021
9	700	20	0.4	0.48	0.025	6.375	32.041

2.2. S/N ratio

Based on Table 3, the S/N ratios are determined for the response variables surface roughness and tool wear in Minitab. It is known that the higher the S/N ratio, the more optimal is the condition. It is observed that for surface roughness, the optimal condition will be cutting speed (700 rpm), feed rate (15mm/min) and depth of cut (0.2mm). But for tool wear, the optimal condition will be cutting speed (700 rpm), feed rate (20 mm/min) and depth of cut (0.4mm).

2.3. Analysis of Variance

The analysis from table 4 shows that all the factors have significant contribution for surface roughnes as all P-Value > 0.05 rejecting null hypothesis. However Feed rate has a major and most significant contribution in determing the surface roughness whose F-value is 2.78. However, the response variable surface roughness predicts smaller effect on the machining of Inconel 718 (R-sq (adj) = 40.77%).

Table 4 Anova for Surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting speed (rpm)	2	0.09847	0.04923	1.88	0.347
Feed Rate (mm/min)	2	0.14540	0.07270	2.78	0.264
Depth of cut (mm)	2	0.05687	0.02843	1.09	0.479
Error	2	0.05227	0.02613		
Total	8	0.35300			
Note: S=0.16168	R-sq= 85.9%		R-sq (adj)= 40.77%		

The analysis from table 5 shows that all the factors have significant contribution for surface roughnes as all P-Value < 0.05. However Depth of cut has a major and most significant contribution in determing the tool wear whose F-value is 255.77. However, the response variable tool wear predicts higher effect on the machining of Inconel 718 (R-sq (adj) = 93.73%).

Table 5 Anova for Tool wear

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting speed (rpm)	2	111.89	55.945	27.85	0.035
Feed Rate (mm/min)	2	154.80	77.398	38.52	0.025
Depth of cut (mm)	2	1027.77	513.883	255.77	0.004
Error	2	4.02	2.009		
Total	8	1298.47			
Note: S=1.41744	R-sq= 99.69%		R-sq (adj)= 93.73%		

2.4. Grey Relational Analysis

Step 1: Setting up the Eigen-value matrix, input original data

An Eigen value matrix is setup according to the experimental run and the corresponding influence factors. In the corresponding values of the matrix, m represents the number of listed experimental runs and n represents the number of influence factors.

Step 2: Standardized data transformation using formulas

After the first step all the values are subjected to a transformation process. This transformation process is based on the influence factors. Influence factors refer to the output parameters of the experiment. The influence factors are surface roughness and tool wear. Table 6 is formulated using the smaller the better (Defect type factor).

$$\text{Defect Type Factor } \mathrm{Xm(n)} = \frac{\max|\mathrm{Xm(n)}| - \mathrm{Xm(n)}}{\max|\mathrm{Xm(n)}| - \min|\mathrm{Xm(n)}|} \quad (1)$$

Table 6 Transformed data using equation (1)

	Original Data		Standardized Transformed Data	
Experimental Run	Surface Roughness (µm)	Tool wear (mm)	Surface Roughness (µm)	Tool wear (mm)
1	0.78	0.050	0.177	0.934
2	0.62	0.025	0.435	1.000
3	0.44	0.057	0.726	0.916
4	0.89	0.040	0.000	0.960
5	0.78	0.148	0.177	0.676
6	0.36	0.050	0.856	0.934
7	0.54	0.405	0.564	0.000
8	0.27	0.050	1.000	0.934
9	0.48	0.025	0.661	1.000

Step 3: Calculation of Grey Relational Degree

- Selection of the best value for each influence factor.
- Getting the absolute difference of compared series and referential series.
- Find out the minimum and maximum.
- Choose the constant p = 0.05.
- Calculation of relational co-efficient and relational degree using equation (2) and (3)

$$\text{Relation coefficient } \tau_m(n) = \frac{\Delta \min + p\Delta \max}{\Delta X_m(n) + p\Delta \max} \quad (2)$$

$$\text{Relational degree } r_m(n) = \Sigma |\omega \tau_m| \quad (3)$$

Table 7 Relational degree and ranking

Experimental Run	Surface Roughness (µm)	Tool wear (mm)	Relational Degree	Rank
ω	0.4	0.6	-	-
τ_1	0.566	0.969	0.808	7
τ_2	0.922	0.873	0.893	4
τ_3	0.853	1.000	0.941	2
τ_4	0.448	0.929	0.737	9
τ_5	0.566	1.710	1.252	1
τ_6	0.660	0.969	0.845	6
τ_7	1.343	0.570	0.879	5
τ_8	0.527	0.969	0.792	8
τ_9	1.000	0.873	0.924	3

3. Results and discussion

Analysis of variance proves through the Figure 4 depicts higher cutting speed (700 rpm), higher feed rate (20 mm/min) and low depth of cut (0.2 mm) will show minimum surface roughness during the machining of Inconel 718 using tungsten carbide as cutting tool. However Figure 5 depicts lower cutting speed (500 rpm), higher feed rate (20 mm/min) and medium depth of cut (0.4 mm) will give minimum tool wear.

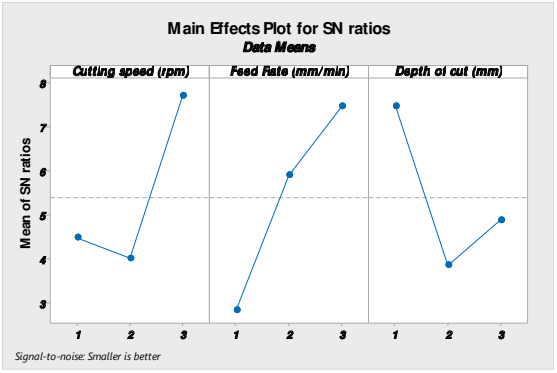

Figure 5 Main effect plot for surface roughness

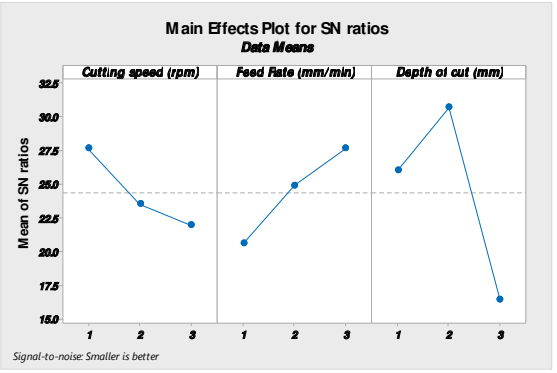

Figure 6 Main effect plot for tool wear

Grey relational analysis found out that for obtaining minimum surface roughness and low tool wear, the ideal optimal conditions for machining Inconel 718 using tungsten carbide are cutting speed (600 rpm), feed rate (15 mm/min) and depth of cut (0.6 mm).

Table 8 Ranking of the experimental runs

Rank	1	2	3	4	5	6	7	8	9
Experimental Run	5	3	9	2	7	6	1	8	4

4. Conclusion

The machinability of Inconel 718 can be greatly enhanced by providing optimal process parameters and giving the cutting speed, feed rate and depth of cut which are the suitable conditions for providing minimum surface roughness and low tool wear. Analysis of variance and Grey relational analysis are the effective tools in optimizing the control factors and determing the suitable response values. Tungsten carbide insert can machine Inconel 718 when the optimal conditions are met and suitable parameters are identified.

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References

[1] Sarmad Khan, Sein Soo, David Aspinwall, Sage, Peter Harden, Fleming, Allan White and Saoubi (2012) "Tool wear/life evaluation when finish turning Inconel 718 using PCBN tooling," *5th CIRP Conference on High Performance Cutting*, **1**, 283-288.

[2] Xavior, Manohar, Jeyapandiarajan and Patil Mahesh Madhukar (2017), "Tool wear assessment during machining of inconel 718," *13th Global Congress on Manufacturing and Management*, **174**, 1000-1008.

[3] Venkatesan (2017), "The study on force, surface integrity, tool life and chip on laser assisted machining of inconel 718 using Nd:YAG laser source," *Journal of Advanced Research*, **8**, 407-423.

[4] Durul Ulutan, Abram Pleta, Andy Henderson, Laine Mears (2015), "Comparison and cost optimization of solid tool life in end milling nickel based super alloy," *43 Proceeding of North American Manufacturing Research*, **1**, 522-533.

[5] Ivan Sunit Rout and P.Pal Pandian (2018), "A Review on Parametric Study of Hard Machining of Inconel 718 using coated carbide tool," Advanced Science, Engineering and Medicine, **10**, 234-239.

[6] Ivan Sunit Rout , Jitendra Narayan Biswal, Biranchi Prasad Mishra (2015), "Experimental Investigation on the Cutting Forces of a Single Point Cutting Tool over Dry Turning Operation", *International Advanced Research Journal in Science, Engineering and Technology*, **2 (7)**,18-24.

[7] P.Pal Pandian, Prabhu Raja, Sakthimurugan (2013), "Optimization of Cutting Parameters of Thin Ribs in High Speed Machining", *International Journal of Engineering Inventions (IJEI)*, **2(4)**, 62-68.

[8] Vaclav Schornika, Miroslav Zetekb, Milan Danac (2015), The Influence of Working Environment and Cutting Conditions on Milling Nickel – Based Super Alloys with Carbide Tools, *25th DAAAM International Symposium on Intelligent Manufacturing and Automation*, Procedia Engineering 100, 1262 – 1269.

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PARAMETRIC ANALYSIS OF RESPONSE VARIABLES FOR IMPROVING THE MACHINING CHARACTERISTICS OF INCONEL 718 USING CERAMIC INSERTS

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ABSTRACT

Highly advanced superalloys is being rapidly spreading throughout the globe. It is in need of the hour to produce such materials which are being used in several industries such as petrochemical, biomechanical, aerospace and marine industries. Inconel 718 is one such superalloy which is being used due to its better characteristic features like high corrosion resistance, high temperature loading conditions, thermal fatigue resistance, and cryogenic temperatures. Due to its hardness, tools are resulting in high wear characteristics and low tool life.Machining of Inconel 718 is always carried out using hard inserts such as CVD, tungsten carbide and ceramics. This research is carried out to find the response variables needed for improving the machining of Inconel 718. Experiment was performed in CNC milling machine using ceramics tool. Cryogenic treatment of the tool has been done to improve tool life. Analysis of variance (ANOVA) has been carried out to predict the response parameters and minimize tool wear.

KEYWORDS: Ceramics Insert, Cryogenic Treatment, CNC Milling, Inconel 718 & ANOVA

Original Article

INTRODUCTION

Background Information

Inconel 718 is a superalloy which has a wide application in different industrial fields. It is used at elevated temperatures and sustains high thermal fatigue strength, crack resistance and thermal shocks. Due to this superior performance characteristics which makes it almost difficult to machine resisting in tool wear and increase in roughness of the surface [1].

Ceramics is one such tool which has identified itself in improving the tool wear behavior and surface characteristics. It showed high oxidation strength and thermal resistance during machinability of Inconel 718. However since the temperature of machining Inconel 718 reaches to almost 650^0C it also showed few behavior of wavy edges on the metal surface [2]. Then cryogenic cooling of inserts was found to effect the hardness of the tool. The tool hardness increase significantly bringing better machining characteristics and improved tool life.

The cryogenic treated insert showed better performance and increased the surface topography features to mirror finish. Even though the tool-workpiece interaction predicted heat index more but cryogenic insert reduced this heat index to almost negligible during machining of Inconel 718 [4].

ANOVA optimization technique was used in the research work to compare results. Ceramics and cryogenic treated ceramics inserts have been used to machine Inconel 718 and prove the better output results.

MATERIAL AND EXPERIMENTATION

"Inconel 718 shown in figure 1 is the workpiece material. The dimensions are 75 mm x 60 mm x 50 mm". The composition of Inconel 718 is shown in table 1.

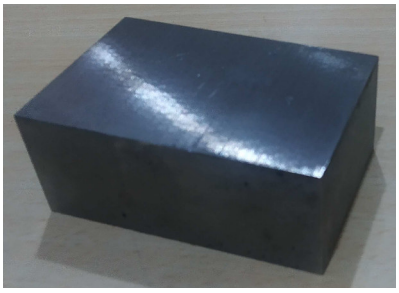

Figure 1: Workpiece (Inconel 718).

Table 1: Inconel 718 Composition [1]

Element	Fe	Co	S	Al	Mb	C	Mn	Cb	Ti	Cr	Ni
%	17.0	1.0	0.35	0.8	3.0	0.08	0.35	5.0	0.6	19.0	52.82

Ceramics is one of the hardest tool being used to machine Inconel 718 for its high toughness and high tool rigidity to withstand high temperatures during cutting operation. It can cut this hard material with ease providing better surface topography and without much wear behaviour on its rake surface. It is round insert of RPGX 1204-GH of grade AS20 shown in figure 2.

Figure 2: Ceramics Insert.

"The experimental study was carried out using CNC vertical milling machine. Specifications of milling machine are spindle speed 1800 rpm, feed rate 10 m/min and power of 25 kW".

Figure 3: Vertical milling CNC Machine.

"An experimental run was carried out using L9 orthogonal array. The cutting parameters are Depth of cut, cutting speed and feed rate, which is shown in table 2. The response parameter are tool wear and surface roughness. Ceramics

insert and cryogenic treated ceramics insert are being used to machine Inconel 718 using CNC milling machine".

Table 2: Control Factors and their Levels [1]

Parameter	Level 1	Level 2	Level 3
Cutting Speed (v) in rpm	500	600	700
Feed Rate (f) in mm/min	10	15	20
Depth of cut (d) in mm	0.2	0.4	0.6

Table 3: Experimentation with the Response Variables of Ceramic Insert

Sl. No.	Cutting Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Surface Roughness (µm)	Tool Wear (mm)
1	500	10	0.2	1.63	0.925
2	500	15	0.4	1.67	1.070
3	500	20	0.6	1.15	1.087
4	600	10	0.4	1.69	0.022
5	600	15	0.6	1.18	1.043
6	600	20	0.2	0.96	0.035
7	700	10	0.6	1.75	0.153
8	700	15	0.2	0.90	0.835
9	700	20	0.4	1.38	0.042

Table 4: Experimentation with the Response Variables of Cryogenic Treated Ceramic Insert

Sl. No.	Cutting Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Surface Roughness (µm)	Tool Wear (mm)
1	500	10	0.2	1.01	0.085
2	500	15	0.4	1.23	0.102
3	500	20	0.6	1.19	0.042
4	600	10	0.4	0.81	0.022
5	600	15	0.6	1.53	0.030
6	600	20	0.2	1.39	0.365
7	700	10	0.6	1.02	2.180
8	700	15	0.2	1.24	1.220
9	700	20	0.4	1.17	0.877

ANOVA for Ceramics Insert

"Regression analysis results are shown in table 5. As the P value is less than 0.05, all the input parameters have considerable effect on surface roughness. Most contributing factor that influenced surface roughness is feed rate as the F-value is 6.46 as shown in table 5. The R sq value is 91% shows the vaiablity of result. Table 6 shows the response for means of surface roughness".

Table 5: ANOVA for Means of Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	0.06727	0.06727	0.03363	0.90	0.025
Feed rate (mm/min)	2	0.48087	0.48087	0.24043	6.46	0.034
Depth of cut (mm)	2	0.26480	0.26480	0.13240	3.56	0.029
Residual Error	2	0.07447	0.07447	0.03723		
Total	8	0.88740				

Note: S=0.1930 R-sq= 91.61%

Table 6: Response Table for Means of Surface Roughness

Level	Cutting Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
1	1.483	1.690	1.160
2	1.277	1.247	1.580
3	1.340	1.163	1.360
Delta	0.207	0.527	0.420
Rank	3	1	2

Regression analysis results are shown in table 7. As the P value is less than 0.05, all the input parameters have considerable effect on tool wear. Most contributing factor that influenced tool wear is cutting speed as the F- value is 7.83. The R sq value is 94.15% shows the vaiablity of result. Table 8 shows the response for means of tool wear.

Table 7: ANOVA for Means of Tool Wear

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	0.9049	0.9049	0.45244	7.83	0.033
Feed rate (mm/min)	2	0.7335	0.7335	0.36677	6.35	0.025
Depth of cut (mm)	2	0.2217	0.2217	0.11085	1.92	0.010
Residual Error	2	0.1156	0.1156	0.05780		
Total	8	1.9757				

Note: S=0.2404 R-sq= 94.15%

Table 8: Response Table for Means of Tool Wear

Level	Cutting Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
1	1.0273	0.3667	0.5983
2	0.3667	0.9827	0.3780
3	0.3433	0.3880	0.7610
Delta	0.6840	0.6160	0.3830
Rank	1	2	3

ANOVA for Cryogenic Treated Ceramics Insert

Regression analysis results are shown in table 9. As the P value is less than 0.05, all the input parameters have considerable effect on surface roughness. Most contributing factor that influenced surface roughness is feed rate as the F- value is 5.80 as shown in table 9. The R sq value is 88.23% shows the vaiablity of result. Table 10 shows the response for means of surface roughness.

Table 9: ANOVA for Means of Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	0.02000	0.02000	0.01000	0.47	0.028
Feed rate (mm/min)	2	0.24847	0.24847	0.12423	5.80	0.047
Depth of cut (mm)	2	0.05287	0.05287	0.02643	1.23	0.044
Residual Error	2	0.04287	0.04287	0.02143		
Total	8	0.36420				

Note: S=0.1464 R-sq= 88.23%

Table 10: Response Table for Means of Surface Roughness

Level	Cutting Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
1	1.1433	0.9467	1.2133
2	1.2433	1.3333	1.0700
3	1.1433	1.2500	1.2467
Delta	0.1000	0.3867	0.1767
Rank	3	1	2

Regression analysis results are shown in table 11. As the P value is less than 0.05, all the input parameters have considerable effect on tool wear. Most contributing factor that influenced tool wear is cutting speed as the F- value is 6.69. The R sq value is 88.36% shows the vaiablity of result. Table 12 shows the response for means of tool wear.

Table 11: ANOVA for Means of Tool Wear

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	3.4801	3.4801	1.7401	6.69	0.023
Feed rate (mm/min)	2	0.2094	0.2094	0.1047	0.40	0.007
Depth of cut (mm)	2	0.2613	0.2613	0.1306	0.50	0.016
Residual Error	2	0.5202	0.5202	0.2601		
Total	8	4.4711				

Note: S=0.5100 R-sq= 88.36%

Table 12: Response Table for Means of Tool Wear

Level	Cutting Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
1	0.07633	0.76233	0.55667
2	0.13900	0.45067	0.33367
3	1.42567	0.42800	0.75067
Delta	1.34933	0.33433	0.41700
Rank	1	3	2

OBSERVATIONS AND DISCUSSIONS

The research conducted on milling of Inconel 718 using ceramic and cryogenically treated ceramic insert helped in identifying better cutting conditions. ANOVA proved to be very efficient in optimizing the input parameters and finding its effects on output parameters. Figure 4 shows the mean of means of surface roughness compared to input variables in three levels. From the graph below we have to assume that lower the surface roughness is better. It shows that an optimized condition of surface roughness is arrieved when cutting speed is at 500 rpm, feed rate is at 10 mm/min and high depth of cut is at 0.4 mm.

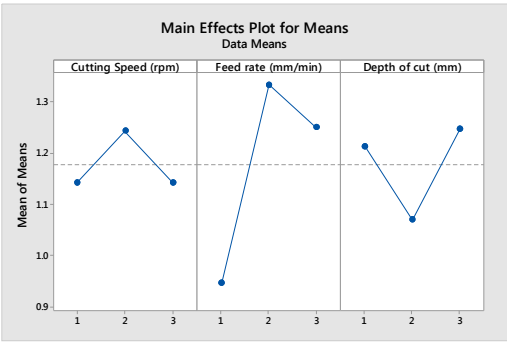

Figure 4: Main Effect Plot for Surface Roughness of Ceramic Insert.

Figure 5 shows the surface roughness during machining of Inconel 718 using cryogenic treated ceramic insert. The graph shows that cutting speed at 600 rpm, feed rate at 20 mm/min and depth of cut at 0.2 mm, derives minimum surface roughness.

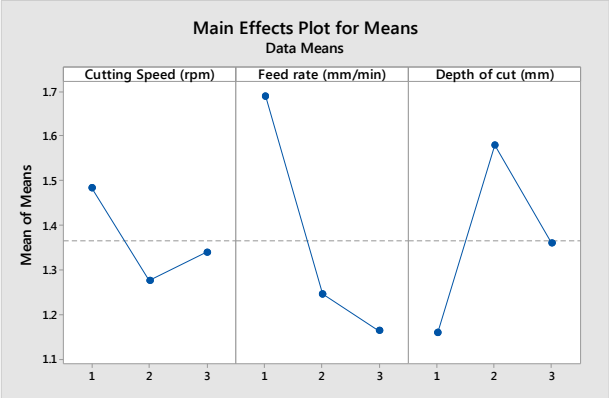

Figure 5: Main Effect Plot for Surface Roughness of Cryogenic Treated Ceramic Insert.

From the figure 6 minimum tool wear happened when cutting speed is at 700 rpm, feed rate at 10 mm/min and depth of cut at 0.4 mm. This machining process used ceramic insert for milling of Inconel 718.

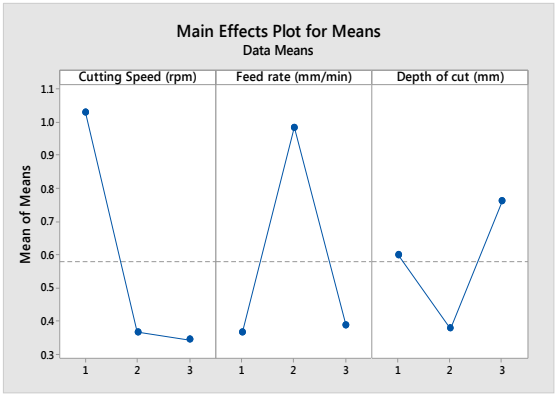

Figure 6: Main Effect Plot for Tool Wear of Ceramic Insert.

The graph in figure 7 shows minimum tool wear when cryogenic treated ceramic insert during machining of Inconel 718. The levels of input parameters are cutting speed at 700 rpm, feed rate 10 mm/min and depth of cut (0.4 mm).

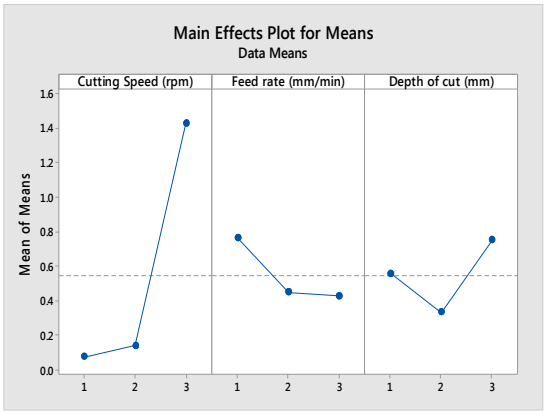

Figure 7: Main Effect Plot for Tool Wear of Cryogenic Treated Ceramic Insert.

Figure 8 predicts that lower cutting speed with low feed rate and low depth of cut shows minimum surface roughness for cryogenic treated ceramics insert while higher cutting speed, low feed rate and high depth of cut is suitable for ceramics insert which showed minimum surface roughness than cryogenic treated ceramics insert.

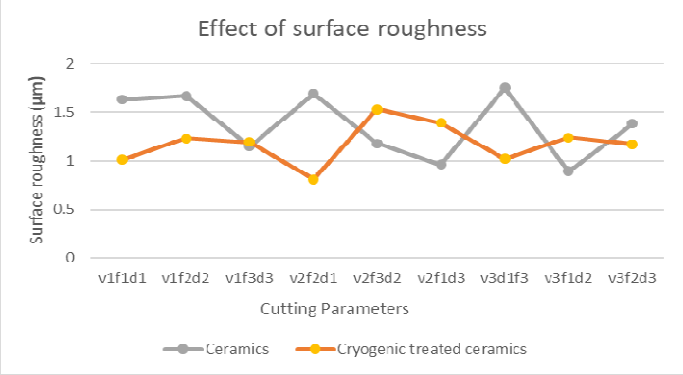

Figure 8: Effect of Surface Roughness on the Cutting Inserts.

Figure 9 predicts that lower cutting speed with high feed rate and high depth of cut shows minimum tool wear for cryogenic treated ceramics insert while higher cutting speed, medium feed rate and high depth of cut is suitable for ceramics insert which showed minimum tool wear than cryogenic treated ceramics insert.

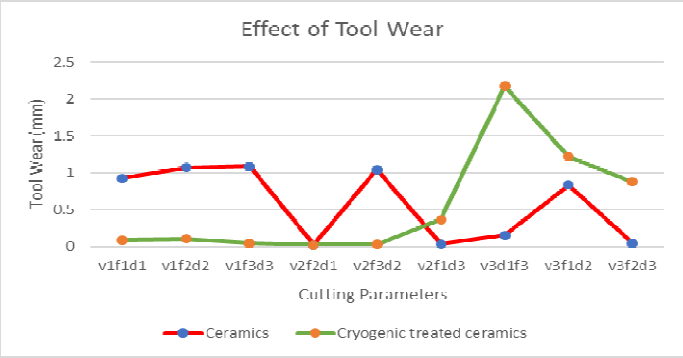

Figure 9: Effect on the Cutting Inserts for Wear of the Tool.

CONCLUSIONS

Ceramics insert showed remarkable results in increasing the machining features of Inconel 718. However, cryogenic treated insert increased the mechanical properties of insert proving minimum tool wear at maximum feed rate and maximum depth of cut. Cutting speed being significant parameter for improving tool life was seen ideal for ceramics insert during machinability conditions. Ceramics insert proved to be a better tool for improving the surface topography of Inconel 718.

REFERENCES

1. *P Pal Pandian, Ivan Sunit Rout: "Parametric investigation of machining parameters in determining the machinability of Inconel 718 using taguchi technique and grey relational analysis", Procedia Computer Science, Vol. 133, pp. 786–792, 2018.*
2. *Ramya R, Ivan Sunit Rout, Lee Yongmin, Manoj Kumar, Abhishek Joseph John: "Optimization of Cutting Parameters for the Machining of Inconel 718 using Grey Relational Analysis", Journal of polymer and composites, STM Journal, Vol.6, Issue 2, pp. 1–5, 2018.*

3. *Pradeep, A., Suryam, L., Prasad, S. S., & Vahini, K. Experimental Investigation and Comparison of Flank Wear and Surface Roughness in Turning Of AISI 4340 Steel using Ceramic Coated and Uncoated Carbide Inserts.*
4. *Kaynak K: "Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining", International Journal of Advanced Manufacturing Technology, Vol. 72, pp. 919–933, 2014.*
5. *D.S.Nadig, G.V.Sathish: " Effect of cryotreatment on the wear performance of tungsten carbide tools", Indian Journal of Cryogenics, Vol. 137 (1-4), pp. 188–193, 2012.*
6. *Yap, H., Pai, Y. S., Chang, S. W., & Yap, K. S. Development of an Augmented Reality-based G-Code Generator in a Virtual CNC Milling Simulation.*
7. *A.S.Chopra, G.V.Sargade: "Metallurgy behind the Cryogenic Treatment of Cutting Tools: An Overview", 4th International Conference on Materials Processing and Characterization, Vol. 2, pp. 1814–1824, 2015.*
8. *V Schornik, M Zetek, M Dana: "The influence of working environment and cutting conditions on milling nickel based superalloys with carbide tools", Procedia Engineering 100, pp 1262–1269, 2015.*
9. *Yunus, M. O. H. A. M. M. E. D., & Alsoufi, M. S. (2015). A statistical analysis of joint strength of dissimilar aluminium alloys formed by friction stir welding using taguchi design approach, anova for the optimization of process parameters. IMPACT: International Journal of Research in Engineering & Technology (IMPACT: IJRET), 3(7), 63–70.*
10. *W.S. Lin, "The reliability analysis of cutting tools in the HSM processes", International Scientific Journal published by the World Academy of Materials and Manufacturing Engineering, Vol.30, Issue 2, pp. 97–100, 2008.*
11. *Ramesh Kannan C, Prathap J, "Experiment investigation of tool wear in turning of Inconel 718 material – Review", International Journal of Advance Engineering and Research Development, Vol. 02, Issue 9, pp. 2348–6406, 2015.*
12. *Chauhan, S. S., Ajitsaria, S. K., Kumar, G., & Khan, M. D. Compact Human Arm for Medical and Industrial Use.*
13. *Nandkumar N. Bhopale, Raju S. Pawade,"Modeling and Analysis of Ball End Milling Parameters of Inconel 718 Cantilevers Using RSM", International Journal of Innovative Research in Science, Engineering and Technology, Vol. 03, pp. 2319–8753, 2014.*
14. *T. Tamizharasan, "Numerical simulation of effects of machining parameters and tool geometry using DEFORM-3D: Optimization and experimental validation", World Journal of Modelling and Simulation, Vol. 10, pp. 49-59, 2014.*

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AN APRROACH FOR THE INVESTIGATION OF CUTTING PARAMETERS TO IMPROVE THE MACHINABILITY OF INCONEL 718 USING CRYOGENIC TREATED TUNGSTEN CARBIDE

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ABSTRACT

Inconel 718 is a nickel-chromium based super alloy and is one of the hardest material to cut. It has high thermal resistance, high creep, high corrosion resistance and retains toughness and strength at elevated temperatures. Due to these mechanical properties the tool life is extremely short. This superalloy has a wide industrial application in the field of bio medical industry, avionics industry, bearing industry, steam turbine and nuclear applications. Tungsten carbide is one such cutting tool being used in the machining of this metal and undergoing cryogenic treatment has helped to increase the machinability. The objective of this study is to investigate the cutting parameters for determining the machinability of Inconel 718 using cryogenic treated tungsten carbide based on Grey Relation Analysis (GRA) and signal to noise (S/N) ratio. The input parameters such as feed rate, cutting speed and depth of cut are taken into account to obtain the optimum output parameters such as minimal surface roughness and low tool wear rate to improvise the machining characteristics of this superalloy.

KEYWORDS: Cryogenic, Tungsten Carbide, GRA & S/N Ratio

Original Article

INTRODUCTION

Computer Numerical control (CNC) machine is a highly advanced programmable machine which has found wide application in industries for manufacturing a variety of products such as cam, shaft, dies, bearings, bushes. This machine has a notable features of creating complex shapes with better dimensional tolerances and high accuracy. It also provides better machinability than conventional machines. [1].

Inconel 718 is a nickel based super alloy with difficult to cut a machine behavior due to its hardness and high thermal strength. Because of its superiority in hardness it is used in industries such as aerospace, marine, biomechanical, chemical and petroleum [2]. This property makes the machining difficult for which all the tools has failed in providing better machining parameters. Tungsten carbide is one the such tool which evolves as a suitable tool for providing low tool wear and minimal surface roughness. Even though this tool have been used, higher temperature conditions have made this tool to provide higher cutting forces and deformations during the machinability.

Cryogenic treated tungsten carbide has not only improved the life of the tool but also provided better strength and thermal resistance in machining Inconel 718 [3]. The present study is to predict the machining parameters that improve tool life of cryogenic treated tungsten carbide tool and provide minimal surface roughness which can be optimized through grey relational analysis and signal to noise ratio (S/N).

MATERIAL AND EXPERIMENTATION

Inconel 718 is the workpiece used in the form of a block where the dimensions are 75mm (length), 60mm (width) and 50mm (height). The tool used is tungsten carbide RYMX 1004-ML of grade TT3540 in round shape [2]. CNC vertical milling machine is used under wet milling conditions. The workpiece is clamped in the working bench vice. The following cutting parameters are used during the machining of Inconel 718 as shown in table 1.

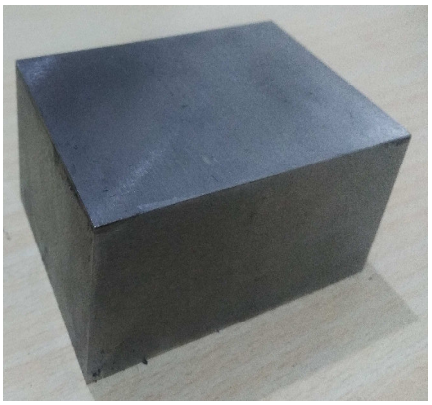

Figure 1: Inconel 718 Workpiece.

Figure 2: Cryogenic Treated Tungsten Carbide.

Table 1: Cutting Parameters and their Levels [2]

Parameter	Unit	Symbol	Level 1	Level 2	Level 3
Cutting Speed	rpm	v	500	600	700
Feed Rate	mm/min	f	10	15	20
Depth of cut	mm	d	0.2	0.4	0.6

Analysis of variance for S/N ratio and means are used through MINITAB 18 software for determining the influence of cutting parameters during machining of Inconel 718.

Table 2: Analysis of Variance for S/N Ratios of Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	5.413	5.413	2.706	0.59	0.042
Feed rate (mm/min)	2	2.890	2.890	1.445	0.32	0.022
Depth of cut (mm)	2	4.087	4.087	2.044	0.45	0.035
Residual Error	2	9.157	9.157	4.578		
Total	**8**	**21.546**				

Note: S = 2.1397
R-sq = 57.50%
R-sq (adj) = 41.77%

Table 3: Response Table for S/N Ratios of Surface Roughness

Level	Cutting Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	0.5283	0.2846	1.3691
2	0.6380	1.0593	0.3609
3	1.3533	0.6883	0.2669
Delta	1.8816	1.3438	1.6360
Rank	1	3	2

The analysis from table 2 shows that all the factors have a significant contribution for the surface roughnes as all

P-Value < 0.05 accepting null hypothesis. However cutting speed has a major and most significant contribution as shown in Table 3 in determing the surface roughness, where F-value is 0.59. However, the response variable surface roughness predicts the smaller effect on the machining of Inconel 718 (R-sq (adj) = 41.77%).

Table 4: Analysis of Variance for S/N Ratios of Tool Wear

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	929.43	929.43	464.71	10.29	0.048
Feed rate (mm/min)	2	61.79	61.79	30.90	0.68	0.029
Depth of cut (mm)	2	101.33	101.33	50.67	1.12	0.037
Residual Error	2	90.36	90.36	45.18		
Total	**8**	**1182.92**				

Note: S = 6.7217
R-sq = 92.36%
R-sq (adj) = 69.44%

Table 5: Response Table for S/N Ratios of Tool Wear

Level	Cutting Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	29.438	20.712	25.102
2	6.661	24.268	16.885
3	26.745	17.863	20.856
Delta	22.777	6.405	8.218
Rank	1	3	2

The analysis from Table 4 shows that all the factors have a significant contribution for tool wear as all P-Value < 0.05 accepting null hypothesis. However cutting speed has a major and most significant contribution as shown in Table 5 in determing the tool wear, where F-value is 10.29. However, the response variable tool wear predicts the higher effect on the machining of Inconel 718 (R-sq (adj) = 69.44%).

Table 6: Analysis of Variance for Means of Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	0.07136	0.07136	0.03568	0.54	0.046
Feed rate (mm/min)	2	0.03536	0.03536	0.01768	0.27	0.029
Depth of cut (mm)	2	0.05716	0.05716	0.02858	0.43	0.039
Residual Error	2	0.13262	0.13262	0.06631		
Total	**8**	**0.29649**				

Note: S=0.2575
R-sq= 55.27%
R-sq (adj)= 46.78%

Table 7: Response Table for Means of Surface Roughness

Level	Cutting Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	1.0767	1.0400	0.8567
2	0.9467	0.8867	0.9767
3	0.8600	0.9567	1.0500
Delta	0.2167	0.1533	0.1933
Rank	1	3	2

The analysis from Table 6 shows that all the factors have a significant contribution for surface roughnes as all P-Value < 0.05 accepting null hypothesis. However cutting speed has a major and most significant contribution as shown in Table 7 in determing the surface roughness, where F-value is 0.54. However, the response variable surface roughness predicts the smaller effect on the machining of Inconel 718 (R-sq (adj) = 46.78%).

Table 8: Analysis of Variance for Means of Tool Wear

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed (rpm)	2	0.340163	0.340163	0.170081	16.51	0.043
Feed rate (mm/min)	2	0.001965	0.001965	0.000982	0.44	0.014
Depth of cut (mm)	2	0.005189	0.005189	0.002594	1.17	0.036
Residual Error	2	0.004446	0.004446	0.002223		
Total	**8**	**0.351762**				

Note: S=0.0471
R-sq= 68.74%
R-sq (adj)= 64.94%

Table 9: Response Table for Means of Tool Wear

Level	Cutting Speed (rpm)	Feed Rate (mm/min)	Depth of cut (mm)
1	0.03400	0.18467	0.16367
2	0.46467	0.17633	0.22200
3	0.07333	0.21100	0.18633
Delta	0.43067	0.03467	0.05833
Rank	1	3	2

The analysis from Table 8 shows that all the factors have a significant contribution for tool wear as all P-Value < 0.05 accepting null hypothesis. However cutting speed has a major and most significant contribution as shown in Table 9 in determing the tool wear, where F-value is 16.51. However, the response variable tool wear predicts the higher effect on the machining of Inconel 718 (R-sq (adj) = 64.94%).

Grey Relational Analysis (GRA)

This optimization technique helps to develop co-relation between the cutting parameters and response variables and also discovers the suitable parameter for determining the machining of Inconel 718 [2].

Step 1 Setting up the eigen value matrix and input the original data

Table 10: Experimentation with Cutting Parameters and Response Variables

Sl. No	Cutting speed (rpm)	Feed Rate (mm/min)	Depth of cut (mm)	Surface Roughness (µm)	Tool wear (mm)
	A	B	C	X	Y
1	500	10	0.2	0.94	0.032
2	500	15	0.4	0.96	0.040
3	500	20	0.6	1.33	0.030
4	600	10	0.4	1.21	0.470
5	600	15	0.6	0.85	0.477
6	600	20	0.2	0.78	0.447
7	700	10	0.6	0.97	0.052
8	700	15	0.2	0.85	0.012
9	700	20	0.4	0.76	0.156

Step 2: Standardized data transformation using formulas

Using Table 10 the data is transformed into standardized form with the formula smaller the better.

Defect Type Factor $Xm(n) = \frac{\max|Xm(n)| - Xm(n)}{\max|Xm(n)| - \min|Xm(n)|}$ (1)

Table 11: Transformed Data using Equation (1)

	Original Data		Standardized Transformed Data	
Experimental Run	**Surface Roughness (µm)**	**Tool wear (mm)**	**Surface Roughness (µm)**	**Tool wear (mm)**
1	0.94	0.032	0.68	0.956
2	0.96	0.040	0.65	0.939
3	1.33	0.030	0.00	0.961
4	1.21	0.470	0.21	0.015
5	0.85	0.477	0.84	0.000
6	0.78	0.447	0.96	0.064
7	0.97	0.052	0.63	0.914
8	0.85	0.012	0.84	1.000
9	0.76	0.156	1.00	0.690

Step 3 Selection of the best value for each influence factor

The best value for each influence factor is selected. Hence the least value of surface roughness and tool wear is selected and chosen as the referential series for further calculation.

Table 12: Referential Series and the Standardized Data

Experimental Run	**Surface Roughness (µm)**	**Tool wear (mm)**
X_0	0.21	0.015
1	0.68	0.956
2	0.65	0.939
3	0.00	0.961
4	0.21	0.015
5	0.84	0.000
6	0.96	0.064
7	0.63	0.914
8	0.84	1.000
9	1.00	0.690

Step 4 Getting the absolute difference of compared series and referential series

The difference between the obtained standardized data and the referential series are found. This is done to indicate the relational degree between two measurement sequences.

$$\Delta Xm(n) = I X_{0(n)} - X_{m(n)} I \quad (2)$$

Table 13: Absolute difference and Compared Series

Experimental Run	**Surface Roughness (µm)**	**Tool wear (mm)**
1	0.47	0.941
2	0.44	0.924
3	0.21	0.946
4	0.00	0.000
5	0.63	0.015
6	0.75	0.049
7	0.42	0.899
8	0.63	0.985
9	0.79	0.675

Step 5 Find out the minimum and maximum to choose the constant p

The maximum and minimum value of each influence factor is found from Table 13 and p value is set as 0.4 for

surface roughness and 0.6 for tool wear which has to be between 0 and 1.

Step 6 Calculation of relational co-efficient and relational degree using equation (3) and (4)

Relation coefficient $\tau_m(n) = \frac{\Delta \min + p\Delta \max}{\Delta X_m(n) + p\Delta \max}$ (3)

Relational degree $r_m(n) = \Sigma | \omega \tau_m |$ (4)

Table 14: Relational Degree and Ranking

Experimental Run	Surface Roughness (µm)	Tool wear (mm)	Relational Degree	Rank
ω	0.4	0.6	-	-
τ_1	0.67	0.395	0.505	7
τ_2	0.69	0.400	0.516	6
τ_3	1.00	0.394	0.636	4
τ_4	1.66	1.025	1.279	1
τ_5	0.56	1.000	0.824	2
τ_6	0.49	0.947	0.764	3
τ_7	0.71	0.407	0.528	5
τ_8	0.56	0.384	0.454	9
τ_9	0.47	0.479	0.475	8

RESULTS AND DISCUSSIONS

Analysis of variance proves through the figure 3 which depicts higher cutting speed (700 rpm), medium feed rate (15 mm/min) and low depth of cut (0.2 mm) will show minimum surface roughness during the machining of Inconel 718 using cryogenic treated tungsten carbide as a cutting tool.

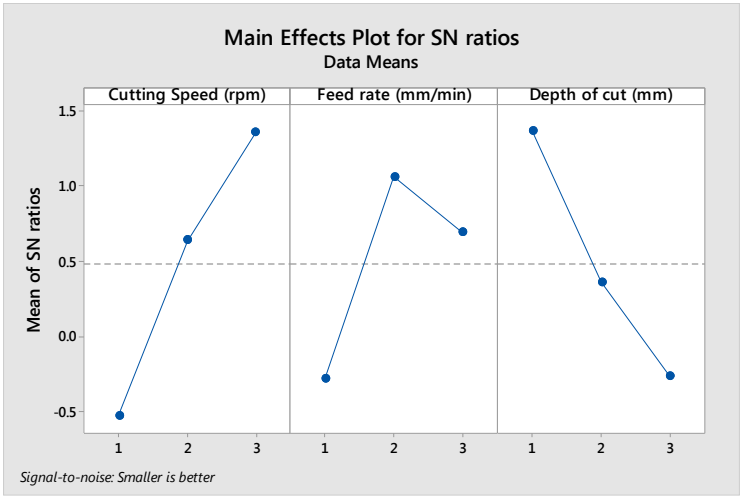

Figure 3: Main Effect Plot for S/N Ratios for Surface Roughness.

However, Figure 4 depicts lower cutting speed (500 rpm), medium feed rate (15 mm/min) and low depth of cut (0.2 mm) will give a minimum tool wear.

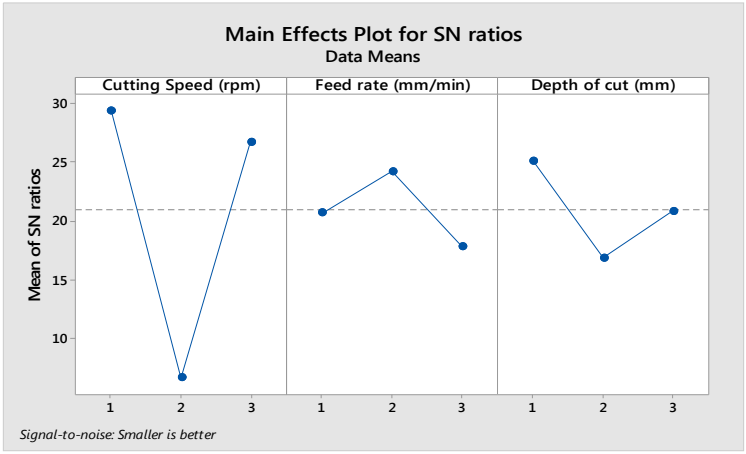

Figure 4: Main Effect Plot for S/N Ratios for Tool Wear.

Figure 5 depicts lower cutting speed (500 rpm), medium feed rate (15 mm/min) and low depth of cut (0.2 mm) will show minimum surface roughness during the machining of Inconel 718 using cryogenic treated tungsten carbide as a cutting tool.

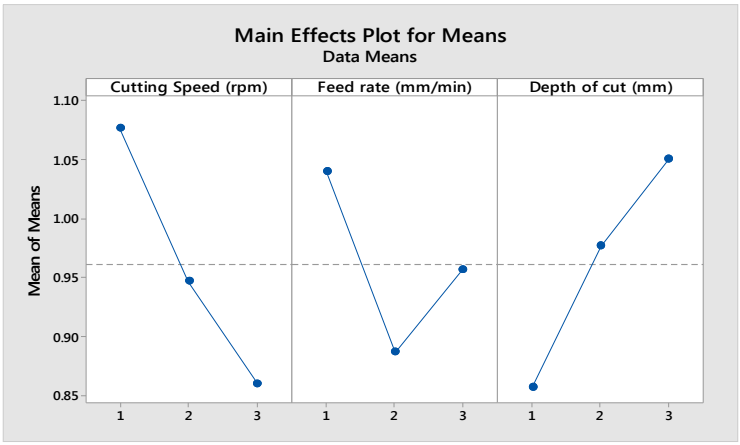

Figure 5: Main Effect Plot for Means for Surface Roughness.

However, Figure 6 depicts medium cutting speed (600 rpm), high feed rate (20 mm/min) and medium depth of cut (0.4 mm) will give a minimum tool wear.

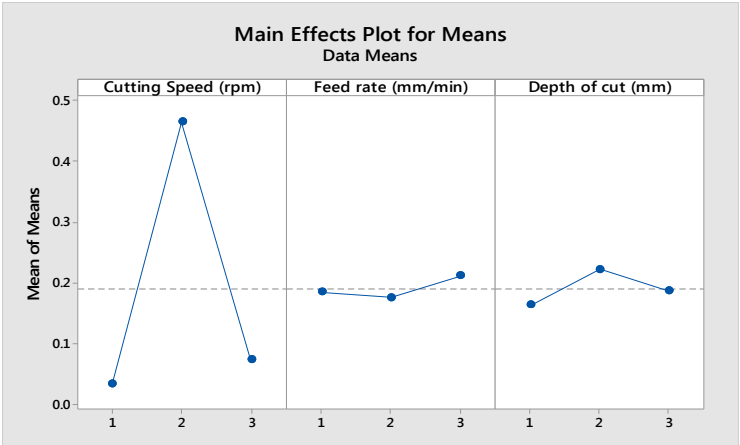

Figure 6: Main Effect Plot for Means for Tool Wear.

Grey relational analysis proved that for obtaining minimal surface roughness and low tool wear the suitable machining parameters were seen in experimental run 4 which has cutting speed 600 rpm, feed rate 10mm/min and depth of cut 0.4mm.

Table 15: Ranking of the Experimental Runs

Rank	1	2	3	4	5	6	7	8	9
Experimental Run	4	5	6	3	7	2	1	9	8

Micro Structural Study

It can be observed clearly, that figure 7 shows the minimum carbide grains present in the tool while Figure 8 shows the increase of size of the grains seen as black dots predicting the increase of hardness and strength while the white patches show the cobalt binder increasing the interatomic strength of the grains improving the tool life.

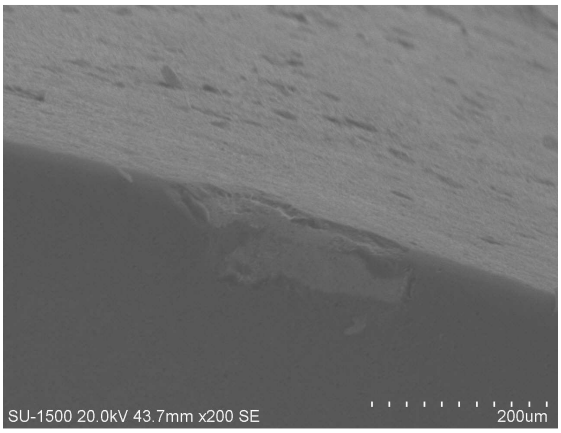

Figure 7: SEM of Tungsten Carbide.

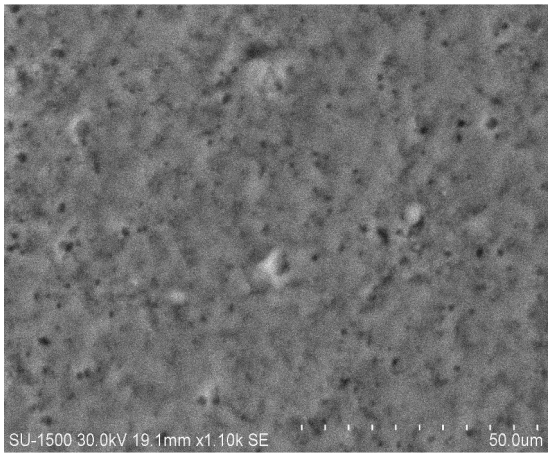

Figure 8: SEM of Cryogenic Treated Tungsten Carbide.

CONCLUSIONS

Cryogenic treated tungsten carbide plays a pivotal role in improving the machinability of Inconel 718 providing minimal surface roughness and a low tool wear. ANOVA for S/N ratio and grey relational analysis determined the machining parameters which are suitable for increasing the performance characteristics. Cryogenic treatment of insert increased the hardness and strength of the tool making Inconel 718 more vulnerable for machining.

REFERENCES

1. *Vishnu Vardhan Mukkoti, G. Sankaraiah, M. Yohan: "Effect of cryogenic treatment of tungsten carbide tools on cutting force and power consumption in CNC milling process", Production and Manufacturing research, Vol. 6, No. 1, pp. 149~170, February 2018.*
2. *P Pal Pandian, Ivan Sunit Rout: "Parametric investigation of machining parameters in determining the machinability of Inconel 718 using taguchi technique and grey relational analysis", Procedia Computer Science, Vol. 133, pp. 786~792, 2018.*
3. *D. S. Nadig, G. V. Sathish: " Effect of cryotreatment on the wear performance of tungsten carbide tools", Indian Journal of Cryogenics, Vol. 137 (1-4), pp. 188~193, 2012.*
4. *Nirmal S Kalsi, Rakesh Sehgal, Vishal S Sharma: " Effect of tempering after cryogenic treatment of tungsten carbide–cobalt bounded inserts", Bullet Material Science, Vol 37, No 2, pp. 327~335, April 2014.*
5. *L. Li, N. He, M. Wang, Z. H. Wang: "High speed cutting of Inconel 718 with coated carbide and ceramic inserts", Journal of materials processing technology, Vol. 129, pp. 127~130, 2002.*
6. *Darshan, C., Singh, P., Saini, S., & Goswami, R. Comparative Evaluation of Untextured and Textured Wc Inserts Under Dry and Near Dry Machining of C45 Steel.*
7. *A. Shokrani, V. Dhokia, S. T. Newman: "Hybrid cooling and lubricating technology for CNC milling of Inconel 718 nickel alloy", 27th International Conference on Flexible Automation and Intelligent Manufacturing, Vol 11, , pp. 625~632, 2007.*
8. *Ivan Sunit Rout, P Pal Pandian: "Selection of cutting parameters for the machinability of Inconel 718 using Grey Relational Analysis", Matec Web of conferences, Vol 172, 2018.*
9. *Nakwong, P., & Muttamara, A. Application of the Taguchi Technique for Wedm Parameters for Tungsten Carbide.*
10. *D. D. Adonna, S. J. Raykar, M. M. Narke: "High speed machining of Inconel 718: tool wear and surface roughness analysis", 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Vol 62, , pp. 269~274, 2017.*

AUTHOR'S PROFILE

Mr Ivan Sunit Rout is currently pursuing his PhD in Mechanical Engineering, CHRIST (Deemed to be University). His research work is in the field of Hard machining and metal cutting. He has 21 International publications, 2 National publications and presented his research work in 10 International conferences. He is the Senior member of Indian society of Mechanical Engineers (ISME). He is a gold medalist in M.Tech in production Engineering. He has won "Best paper" award for presentation in International Conference.

Dr. P. Pal Pandian has received his Ph.D in Mechanical Engineering from Anna University, India. His research interests are in High Speed Machining, Machining of Thin-Walled Structures, Metal Cutting, Dynamics and Vibrations, Design and Manufacturing Engineering. He has 21 International publications in peer-reviewed journals and presented his research work in 15 International conferences. He also has 13 publications in National conferences. He is the recipient of 8 esteemed awards that includes "Best Faculty and Researcher in Mechanical Engineering - Republic Day Achievers Award 2018" from Integrated Intelligent Research (IIR), Chennai, India. He is a member of editorial board in 5 peer-reviewed International Journals and Edition-in-Chief for International Journal of Advanced Research in Management, Engineering and Technology (IJARMET - http://ijarmet.in/).

Dr Anil Raj has received his PhD in Mechanical Engineering from KarunyaInstitute of Technology and Sciences, Coimbatore, India. His research interests are Manufacturing, production and optimization techniques. He has 15 International publications in peer reviewed journals and presented his research work in 10 International conferences.His grade is Fellowin the Indian society of Mechanical Engineers (ISME). He is the CDC member of the Department of Mechanical and Automobile Engineering, CHRIST (Deemed to be University).

Mr Kevin Lobo Ivan is the final year B Tech student of Mechanical Engineering, Department of Mechanical and Automobile Engineering, CHRIST (Deemed to be University). He has presented 4 papers in International conferences and won 2 Best paper awards in the International conferences. He is a very active student whose keen interest is in research of nanocoating and Hard machining.

Mr Shinto Antony C is the final year B Tech student of Mechanical Engineering, Department of Mechanical and Automobile Engineering, CHRIST (Deemed to be University). He is very active in research work. His research interests are Hard machining and metal cutting.

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certificate

This is to certify that ~~Dr./~~Prof./~~Mr./Ms.~~ IVAN SUNIT ROUT

has presented/Participated in the Second International Conference on Mechanical and Manufacturing Engineering (ICMME - 2017) organized by the Department of Mechanical Engineering SCSVMV University on 6th and 7th, April 2017.

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ICDAMS 2018

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OF PARTICIPATION

Presented to

IVAN SUNIT ROUT

For presenting a paper titled Selection of Cutting Parameters For the Machinability of Inconel 718 Using Grey Relational Analysis at the

3rd International Conference on Design, Analysis, Manufacturing and Simulation (ICDAMS 2018)

held during 6 - 7 April 2018, organized by Departments of Mechanical and Automobile Engineering, Saveetha School of Engineering, Saveetha Insitute of Medical and Technical Sciences, Chennai, India.

ICDAMS 2018

Dr. V. Jayakumar
Convener

Dr. D. Devika
Conference Chair

Dr. D. Dhanasekaran
Principal

Certificate of Participation

International Conference on

"Robotics and Smart Manufacturing (RoSMa2018)"

19-21 July 2018

Organized by IIITDM Kancheepuram, Chennai, INDIA

Paper ID: 163

This is to certify that Ivan Sunit Rout, christ university has presented the paper titled, An Approach to Parametric study of Machining Parameters in determing the Machinability of Inconel 718 with optimization Technique during the Conference.

IIITDM, Kancheepuram

Dr. M. Sreekumar
Organizing Chair

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23 - 24 February 2018

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This is to certify that Dr/Mr/Mrs IVAN SUNIT ROUT
from CHRIST (Deemed TO Be University) *has participated and presented a paper titled*
Investigation of Process Parameters in the machining of Inconel-718 with Acazbide tool using Taguchi method
in National Conference on Mechanical Engineering and Emerging Technologies held on 23 - 24 Feburary 2018
at Faculty of Engineering, CHRIST (Deemed to be University), Bengaluru

Dr Gurumoorthy S Hebbar
HOD, Mechanical & Automobile Engineering
Faculty of Engineering

Dr Iven Jose
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This is to certify that Dr./Mr./Ms. IVAN SUNIT RAJ.

of Unist (Deemed to be University) Faculty of Engineering. has presented/~~Keynote~~

~~Address~~ on Parametric Investigation on the tool wear while performing face milling on Inconel 718 using Ground Insert.

in **International Conference on Recent Trends in Advanced Material Processing (ICRTAMP 2019)**

organised by Department of Mechanical Engineering, **Chennai Institute of Technology** on 20th & 21st March 2019.

Convener | Organising Secretary | Principal

Vel Tech
Rangarajan Dr. Sagunthala
R&D Institute of Science and Technology
(Deemed to be University Estd. u/s 3 of UGC Act, 1956)

International Conference on Design, Materials, Cryogenics and Constructions (ICDMC'19)

28th & 29th March 2019

CERTIFICATE OF MERIT

Dr. /Mr. /Ms. IVAN SUNIT ROUT, P PAL PANDIAN

of CHRIST, BANGALORE has been awarded the "Best Paper Award" for the presentation titled AN EXPERIMENTAL ANALYSIS OF MACHINABILITY CHRRACTERISTICS FOR INVESTIGATING THE MACHINABILITY OF INCONEL 718 in the Technical Session MATERIALS of an International Conference on Design, Materials, Cryogenics and Constructions held on 28th & 29th March, 2019, Organised by the School of Mechanical and Construction.

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Session Chair
Global Leader – Materials,
WABCO India Pvt Ltd, Chennai

Dr. N.Lenin & Dr. P.Anand
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This is to certify that Dr. /Mr./Ms. Ivan Sunith Rout *of* Christ University Faculty of Engineering, Bangalore *has presented a paper titled* Development and characterisation of Al-Ti-Cr-N coating on tungsten carbide insert *in the* **International Conference on Advancements in Mechanical Engineering (ICAME 2019)** *held on 10th & 11th of April 2019, organized by the Department of Mechanical Engineering,* **Jyothi Engineering College,** *Thrissur, India, in association with* **Indian Society for Technical Education (ISTE).**

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The Catalysis Society of India

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This is to certify that Prof./Dr./Mr./Ms./ Ivan Sunit Rout from CHRIST (Deemed to be University), Faculty of Engineering has participated/attended the International Conference on Advances in Materials Research (ICAMR-2019) organized by Departments of Chemistry and Mechanical & Manufacturing Engineering, RUAS in association with Catalysis Society of India – Bangalore Chapter at Ramaiah University of Applied Sciences, on 25 – 27 July 2019 as Invited Speaker/ Chairperson / Oral Presenter / Poster Presenter /Delegate.

Title of the Article: Influence of Cryogenic Treatment of Cutting Tool Inserts on Tool Wear and Surface Roughness during Milling of Inconel 718

Prof. Govind R. Kadambi
Chairman – Organizing Committee, ICAMR-2019
Pro-Vice Chancellor - Research
Ramaiah University of Applied Sciences

Dr. T. Niranjana Prabhu
Organizing Secretary, ICAMR-2019
Head-Department of Chemistry
Ramaiah University of Applied Sciences

International Conference on
Advanced Ceramics and Nanomaterials for Sustainable Development

ACeND-2018

CERTIFICATE Of PARTICIPATION

This is to certify that Prof./Dr./Mr./Ms. IVAN S. ROOT, PALPANDIAN P., SHOMYAJIT M., LOBO, VISHAL, SHINTO A. from CHRIST (DEEMED TO BE UNIVERSITY) has presented a paper (Oral/Poster) titled "EXPERIMENTAL STUDY OF RESPONSE PARAMETERS FOR IMPROVING THE MACHINABILITY CHARACTERISTICS OF INCONEL 718 USING CERAMIC INSERTS" in ACeND-2018 held during 19-21, September 2018 at Faculty of Engineering, CHRIST (Deemed to be University), Bengaluru and secured First / Second / Third prize in (Oral/Poster) presentation.

Dr. Dinesh Rangappaa	Dr. Shyam S. Rao	Dr. Gurumoorthy S. Hebbar
Convener	Chairman	Secretary

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Author Workshop jointly organized

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has successfully participated in Author Workshop

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Managing Director
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Dr. Samiksha Shukla
Assistant Professor
CHRIST (Deemed to be University)
Bangalore

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TO WHOMSOEVER IT MAY CONCERN

02nd February 2019

This is to certify that **Mr. Ivan Sunit Rout, Asst. Prof Christ University** has attended the **Two Day Workshop on "Research Methodology and IEEE AuthorshipLab"** organized by the Department of Computer Science [PG], Kristu Jayanti College in association with IEEE ComSoc, Bangalore on February 01st and 02nd , 2019.

Dr. R. Kumar
Head, Department of Computer Science [PG]
Kristu Jayanti College (Autonomous)
Bengaluru - 560077

Prof. R. Kumar
Head, MCA Programme
Department of Computer Science (PG)
Kristu Jayanti College
K. Narayanapura, Kothanur Post
Bengaluru-560 077

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This to certify that Ivan Sunit Rout

has successfully completed the Two days workshop on "Research and modern tools usage" organised by the Department of Mechanical and Automobile Engineering, from 30-05-2019 to 31-05-2019.

Dr. G S Hebbar
Head of the Department
Mechanical and Automobile Engineering

Dr. Iven Jose
Dean
Faculty of Engineering

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Centre for Research - Projects

Approval of Monograph Proposal

10 January, 2018

To,

Dr P Pal Pandian and Prof Ivan Sunit Rout

Dear Sir,

Reg: Your Research Project: **Parametric optimization of hard machining of Inconel 718 using coated tools**

We are pleased to inform you that your Monograph Project proposal under the Scheme has been approved. The project duration shall be 18 months from the start date.

Start Date: December 01, 2017

In this regard you may avail the financial support from the University on the following conditions.

1. The financial support is extended at your request.
2. The financial support of Rs. 3,35,000/- (Rs. Three Lakhs Thirty Five Thousand only) towards Research Expenses has been approved as under:

	Year	Amount
1.	From Dec 2017 to Mar 2018	1,64,000
2.	Apr 2018 to Sep 2018	1,41,000
3.	Oct 2018 to May 2019	30,000
	Total	3,35,000

3. The disbursement will be progressively as under, Payment other than the first payment will be on reimbursement basis.

    - 25% of the First year funding on signing the Agreement of commitment & providing activity plan for the first six months.
    - Up to 50% of the funding for the year on reimbursement basis.
    - Up to 100% of the funding for the year on reimbursement basis.
    - Progressive payments during subsequent years will be on the basis said above.
    - The financial support of Rs. 3500/- (Rs. Three thousand five hundred only) per month (up to the originally approved maximum project period) towards Research allowance will be disbursed Bi-annual in arrears and first disbursement shall be due on satisfactory progress made, at the end of first six months and on that basis for subsequent six month periods.

4. Project Progress Report must be submitted at the end of every six months from the start date till the duration of the project. The report must be submitted in the prescribed format with such enclosure/s as may be specified. The Progress Report must contain relevant details of progress made on investigation preliminaries, data collection including sources and activity plan for the next half yearly. The report must also attach all relevant expense vouchers in support of Research Expenses.
5. You must execute the Agreement of Commitment in the prescribed format.
6. You must submit an Activity Plan for the first six months.
7. You are also requested to open a dedicated Bank Account with SIB Christ University Branch on signing the agreement.

Kindly acknowledge receipt and your acceptance by signing the duplicate of this letter.

Associate Director

Vice Chancellor

PUBLICATION ELIGIBILITY FOR SYNOPSIS PRESENTATION

I. Provide the following information (please fill):-

1. **Name of the Scholar:** Ivan Sunit Rout **Reg. No.:** 1670087 **Batch:** 2016 **Dept.:** Mechanical and Automobile Engineering

   Research Area: Hard Machining of Inconel 718

   Research Title: An investigative approach to hard machining of Inconel 718 with coated carbide tool

   Name & address of your Research Guide/ ~~Co-guide/External Guide~~: Dr P Pal Pandian, Associate Professor, Department of Mechanical and Automobile Engineering, School of Engineering and Technology, CHRIST (Deemed to be University), Bangalore-560074.

   Month & Year of Course Work completion: February 2017

   No. of annual presentations completed (mention dates also): 2 (30 August 2017, 27 September 2018)

   No. of department level seminars presented (Proof -circular & attendance): 4

   Whether monthly progress reports submitted? Yes

   No. of papers published in National Journals: Nil

2. No. of papers published in International Journals: 4
3. No. of presentations in National Conferences: Nil
4. No. of presentations in International Conferences: 5
5. Whether you have published in ~~IEEE Xplore~~/Scopus/~~WOS~~ indexed journals? Yes/ ~~No~~ (Tick)

II. Provide the details in the table below carefully:-

S.No.	Name of Journal and Title of Paper	Whether your Supervisor's name included in publication?	Whether Christ (deemed to be University) affiliation used in publication?	Provide link to view the published version of your paper available in the website, Scopus/ WOS indexed /IEEE Xplore in the website	Month & Year of publication	ISSN/ISBN/ DOI
1	**Journal name:** Advanced Science, Engineering and Medicine **Title of paper** A Review on parametric study of hard machining of Inconel 718 using coated carbide tool	Yes	Yes	Journal link: https://www.scopus.com/sourceid/21100852977 **(Indexed in scopus)** Paper link: https://doi.org/10.1166/asem.2018.2131	March 2018	ISSN: 2164-6627 (P) 2164-6635 (E) DOI:10.1166/asem.2018.2131

2	**Journal name:** MATEC Web of Conferences **Title of paper** Selection of cutting parameters for the machinability of Inconel 718 using Grey Relational Analysis	Yes	Yes	Journal link: https://www.scopus.com/sourceid/21100316064?origin=resultslist **(Indexed in scopus)** Paper link: https://www.matec-conferences.org/articles/matecconf/abs/2018/31/matecconf_icdams2018_04004/matecconf_icdams2018_04004.html	June 2018	ISSN: 2261-223X (E) DOI: https://doi.org/10.1051/matecconf/201817204004
3	**Journal Name:** Procedia Computer Science, Elsevier **Title of Paper:** Parametric Investigation of machining parameters in determining the machinability of Inconel 718 using taguchi technique and grey relational analysis.	Yes	Yes	Journal link: https://www.scopus.com/sourceid/19700182801?origin=resultslist **(Indexed in scopus)** Paper link: https://doi.org/10.1016/j.procs.2018.07.118	July 2018	ISSN: 1877-0509 DOI: 10.1016/j.procs.2018.07.118
4	**Journal Name:** International Journal of Mechanical and Production Engineering Research and Development **Title of Paper:** Parametric analysis of response variables for improving the machining characteristics of Inconel 718 using ceramic inserts	Yes	Yes	Journal link: https://www.scopus.com/sourceid/21100814505?origin=sbrowse **(Indexed in scopus)** Paper link: http://www.tjprc.org/conference-archives.php?tid=&e_type=&jname=&year=&keyword=Ivan+Sunit+Rout&from_date=&to_date=&journal=	December 2019	ISSN: 2249-6890 (P) 2249-8001(E)

5	**Journal Name:** International Journal of Mechanical and Production Engineering Research and Development **Title of Paper:** An approach for the investigation of cutting parameters to improve the machinability of Inconel 718 using cryogenic treated tungsten carbide	Yes	Yes	Journal link: https://www.scopus.com/sourceid/21100814505?origin=sbrowse **(Indexed in scopus)** Paper link: http://www.tjprc.org/conference-archives.php?tid=&e_type=&jname=&year=&keyword=Ivan+Sunit+Rout&from_date=&to_date=&journal=	February 2020	ISSN: 2249-6890 (P) 2249-8001(E)
S.No	**Name of Conference and Title of Paper**	**Whether your Supervisor's name included in publication?**	**Whether Christ (deemed to be University) affiliation used in publication?**	**Provide link to view the published version of your paper available in the website, Scopus/ WOS indexed /IEEE Xplore in the website**	**Month & Year of publication**	**ISSN/ISBN/ DOI**
6	**Conference Name:** Presented on International Conference on Advanced ceramics and nanomaterials for sustainable development (ACeND 2018) **Title of Paper:** Experimental study of response parameters for improving the machinability characteristics of Inconel 718 using ceramic inserts	Yes	Yes	Not available online Souvenir and certificate copy attached	19-21 September 2018	NA
7	**Conference Name:** Presented on International conference on Design, Materials, Cryogenics and Constructions (ICDMC 2019) **Title of Paper:** An experimental analysis of machinability characteristics for investigating the machinability of Inconel 718	Yes	Yes	Not available online Souvenir and certificate copy attached	28-29 March 2019	NA

Note if any, on publications made: 5 papers published in International journals (scopus indexed), 1 chapter publication (under print)

Citations, if any:

1. A Review on parametric study of hard machining of Inconel 718 using coated carbide tool (1 no)

2. Parametric Investigation of machining parameters in determining the machinability of Inconel 718 using taguchi technique and grey relational analysis (1 no)

III. Confirmation:

1. The above information has been filled in concurrence with my research supervisor.
2. The PDF copies of **published version of papers** are also attached.

Signature of Scholar with date: Ivan Sunit Raut 12.2.2020

REMARKS BY THE RESEARCH CENTRE AUTHORITY (FOR OFFICE USE ONLY): (to be filled)

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Dr S Suganthi, Research Coordinator
Name and Signature of Verifier

Date: 13.02.2020